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DEVELOPMENT OF TRACKING ERROR FREQUENCY RESPONSE FUNCTIONS AND AIRCRAFT RIDE QUALITY DESIGN CRITERIA FOR VERTICAL AND LATERAL VIBRATION

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FOREWORD

This report was prepared by John W. Rustenburg, Airframe Division, Deputy for B-1, under System 139A, B-1.

The report covers an intermittent study effort conducted during a period from November 1968 to July 1970.

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This technical report has been reviewed and is approved.

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ABSTRACT

Experience has shown that the aircraft gust sensitivity index $\bar{A}$, defined as the rms acceleration response per unit of rms gust velocity does not provide a consistent measure of ride quality. A ride quality analysis method which includes the effects of vibration frequency and exposure time on human discomfort or performance has been available. This method, however, has been plagued by the lack of clearly defined human frequency response curves and vibration tolerance criteria.

This report presents the results of a study of available experimental literature in order to more clearly define the shape of frequency response functions for human psychomotor performance under vertical and lateral vibration conditions. The performance frequency response functions as developed are based on a constant tracking error and are used in the calculation of a human performance index for some aircraft. Evaluation of human performance index values and associated crew effectiveness estimates are used to determine ride quality criteria in terms of exposure time and crew tolerance levels for vertical, lateral, and combined-axes vibration inputs.

Appendix II presents a comparison of the shape of vertical and lateral performance curves derived in this study with vertical and lateral objectionable discomfort curves derived independently for commercial transport passenger ride quality criteria development. By allowing for soft seat versus hard seat responses, close general agreement in the shapes of the frequency response curves is noted.

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SYMBOLS

$\bar{A}$	aircraft gust sensitivity - rms g/rms FPS
$\bar{H}_e$	crew task performance index - rms error/rms FPS
f	frequency - Hz
L	scale parameter - ft
$T_{a/p}$	airplane frequency response function - g/FPS
T_e	psychomotor task frequency response function - error/g
σ_e	rms task error response - rms error
σ_n	rms acceleration - rms g
σ_u	rms gust velocity - rms FPS
Φ_u	gust power spectral density
Ω	spatial frequency
Λ	sweep angle

SECTION I

INTRODUCTION

Operation at low altitude and high speed (LAHS) for extended periods of time has become an important part of design mission requirements for many military aircraft. Such operation subjects the airframe to a severe turbulence environment to an extent not previously known. The airframe accelerations resulting from this environment can be further aggravated by the aeroelastic behavior of highly elastic aircraft. The effect of the total airframe response on crew comfort and control effectiveness may impose considerable limitations on aircraft performance and mission success.

Although human comfort considerations have always been of concern to the aircraft design engineer, it has now become necessary to actively consider aircraft ride quality criteria and their application to an aircraft design from its inception.

Many investigations have been made both in regard to measuring subjective discomfort as well as certain task efficiencies. However, experimental variations in the definition of discomfort or tasks, the exposure times, vibrational intensities, subject experience, etc. have not resulted in consistent conclusions regarding human response to vibration, especially in the area of performance. On the whole, therefore, most research has resulted in general conclusions, regarding human performance, which although usable as guidelines in aircraft design, have not allowed the ride quality aspects of a design to be put on a firm engineering basis.

A ride quality analysis method which includes the effects of vibration frequency and exposure time on human discomfort or performance has been available, but this method has been plagued by the lack of clearly defined human frequency response functions and vibration tolerance criteria. It was the purpose of the study as presented in this report to review the available experimental literature and attempt to define the shape of frequency response functions for human psychomotor performance under vertical and lateral vibration conditions. In addition, it was desired to develop ride quality design criteria which could be used in the design and evaluation of an acceptable military aircraft crew station vibrational environment.

SECTION II

DERIVATION OF TRACKING ERROR FREQUENCY RESPONSE FUNCTIONS

1. GENERAL EXPERIMENTAL DATA REVIEW

A considerable amount of information regarding human response to vibration appears to have been reported in official reports as well as in various technical and medical journals. A closer study of these sources, however, reveals that often the information is a repetition of the same data and research results in different publications. Furthermore, the information presented in professional journals and periodicals is usually of a very general nature, without presentation of any basic data. Lastly, the use of a statistical analysis of variance of the data often results in discarding the basic data in favor of lumped results when no significant differences can be shown to exist.

This, it is felt, can result in a loss of much usable data. It allows for a possible disregard of effects which can be handled in an engineering analysis in favor of more significant effects which perhaps cannot. It must also be remembered that statistical significance refers only to the probable repeatability of the results from the experiment in question. It reveals nothing regarding the importance of the results or the repeatability under different experimental procedures.

The points discussed above considerably reduced the usable data which was originally thought to exist. Although this reduces confidence in the curves to be developed, sufficient data remains to allow derivation of a constant performance curve over a range of frequencies.

The usable data are the result of vibration experiments exhibiting differences in tasks, seat types and restraints, task complexities, vibration derivation, subject experience and motivation, etc. As many investigators have noted, the differences in these variables make it difficult to make objective comparisons between all the research findings and may underlie the discrepencies among so many experimental results. In the present study some of these variables were approached separately and common trends were noted, in the hope that this would result in a clearer understanding of the important parameters and the derivation of usable human performance response information.

2. DATA ANALYSIS PROCEDURES

a. Vertical Vibration

When we think of crew performance, we think essentially of a crew's ability to perform psychomotor tasks. Such tasks, which include tracking, placing markers on a screen, replacing modules, throwing switches, etc., require precise muscular coordination and are very much frequency dependent. Since tracking performance is an important parameter in light of the LAHS requirement, it was the task chosen in the study to determine a human performance curve. In addition, more data is generally available on this performance parameter, at least for vertical vibration.

As pointed out previously, the measurement of performance is different for the various researchers and can thus not be directly compared. However, the frequency effects on tracking performance, if they exist, could be expected to behave in a similar manner for all experiments. In other words, the change in relative tracking error from one discrete sinusoidal frequency input to another would be identical, even though the total error would be dependent on task complexity, vibration duration, vibration intensity, and other variables mentioned.

To provide a better comparison between studies and a common measuring scale, the performance score for each experiment was expressed as a ratio of the performance error during vibration to the error during nonvibration control conditions.

The tracking performance error as a function of vibration intensity is plotted for various sinusoidal frequencies in Figures 1 to 11. A study of these data plots reveals that the performance appears to level off or even improve at certain intensity values after the initial rapid error increase with the onset of vibration. Weisz (Reference 5) noted that there is some evidence that performance decrements at the lowest vibration amplitudes were different in character and cause from those observed at higher vibration levels, indicating that there is not a single simple continuum between nonvibrational control condition and vibrational levels of operational significance. The intensity value at which this break occurs varies apparently with frequency, and it seems possibl that this phenomenon occurs due to muscular tensing of the subject which in turn reduces his error. Guignard (Reference 13) has shown that a reduction in seat-shoulder transmissibility occurs due to involuntary muscular tensing, which increases with forcing acceleration. It seems reasonable that such damping of bodily movement might affect certain performance improvements.

It is possible to replot the data in Figures 1 to 11 in terms of constant error points against frequency and intensity of vibration. Because at higher levels of intensity the frequency effects on error become more significant and visible, the constant error points are best derived at intensity levels above the error discontinuity due to assumed muscular tensing. Cross plotting can be done at the lower intensity levels; however, at the levels of intensity where the discontinuity occurs, no consistent constant error result can be expected. Figures 12 to 20 show the constant error points for a number of references, and show the expected consistent variation with frequency for each. Observed differences in level are of course the result of the variables mentioned before. In a few cases more than one constant error level was chosen for a reference, where large error variation with frequency occurred. Except for Figures 16 and 19, these were not plotted because they did not significantly affect the final results. It was decided to omit the replotting of the data of Figures 3 and 7. It is, of course, always risky to interpolate between two points only, but the lacl of variation in error for different vibration intensities at the same frequency of Figure 7 suggests that the tests were performed in the area where subject tensing occurs. In addition, the data is confounded by the fact that the vertical task incorporated a feedback delay.

The next step is to combine the many constant error versus frequen elements into a common continuous error response curve. Pradko (Referen 44) has shown that whole body response is reasonably linear within the boun of interest, a fact which seems supported by the curve elements, so that a simple normalization procedure can be used whereby all data points are equated to a common continuous curve. This normalization could be accomplished graphically; however, it was found to be simpler to perform in a tabular form. The approach can best be explained by a description of its application.

First, the data points from Figures 12 to 20 were tabulated by intensity and frequency level. The shaded numbers in Table I represent these values. Additional intensity values were then interpolated or extrapolated to either side of these points not to exceed an increment of one Hertz. At constant frequencies, intensity values between references were written as a ratio, where this was possible. These ratios are shown below the intensity values, and are indicated by R in the table. The subscripts of σ_n / σ_m, in the last column, indicate the reference numbers on which the ratios are based. From these ratios, an average value was determined for each row as shown in Table II. From the average ratio values and using 1 rms g at 1 Hertz as an anchor point, normalization constants (K) were calculated. The K factors are also presented in Table II and represent the differences between experimental results due to endurance time, subject training, task, etc. The intensity values of Figures 12 to 20 were weighted by the K values and the resulting normalized intensity values are tabulated in Table III and plotted in Figure 21.

As can be seen, the points indicate a very consistent variation of intensity with frequency even between vertical, horizontal, and total tracking error. The reason for the apparent dislocation of the two data points at 4 Hertz is not clearly understood. It is very likely that these points are at muscular tensing conditions different from those at other frequencies for the same experiment. The data available does not allow a definite conclusion to be made on this.

It should be noted that there is no inference that the error at different frequencies or between different tracking tasks is due to the same physiological effects. The study did show that the shape of the curves is not significantly affected by exposure time or vibration intensity except at intensity levels where the subject goes from a relaxed condition to a condition of muscular tensing.

One additional fact to emerge from the study was that the shape did not appear to be influenced by the type of controller used, whether it be a wheel and column, a common control stick, a sidearm controller, or even a simple automobile steering wheel.

b. Lateral Vibration

Performance data obtained under conditions of lateral vibration are extremely limited. This is unfortunate in view of the fact that lateral vibration is often considered more detrimental to performance and tolerance than vertical vibration.

Figure 22 presents the available tracking performance for lateral vibration in the same manner as that used in the case of vertical vibration. Figure 23 shows the constant error intensity values.

Needless to say, the scarcity of these experimental data makes the validity of the shape of any tolerance curve derived from the data somewhat questionable. It was decided therefore to study possible relationships between human performance and body transmissibility under vibration conditions to obtain clues to reliability of the curve, and its extrapolation to other frequencies. Such a study was conducted for vertical vibration (not reported in this document) with reasonable success. This study revealed that, for frequencies above 3.5 Hertz, the shape of a constant performance curve was almost identical to the inverse of the average transmissibility for seat-to-head and seat-to-shoulder. At lower frequencies, it appeared to more closely follow the tolerance curve as described by Magid and Goldman.

For the lateral vibration under discussion, a similar approach was followed. Figure 24 presents the shape of a normalized curve as determined by using the average head-seat, shoulder-seat body transmissibility data of References 27 and 28, the low frequency tolerance data from Reference 24 and the constant performance curve of Figure 23. Very good agreement can be noted except for the 5.5 Hertz frequency. Based on the overall agreement, the shape of the curve in the Figure 24 is proposed as a standard for constant tracking error for lateral vibration. Since the data on which this curve is based is very limited, it will be necessary to reevaluate the proposed curve in the future when new experimental data becomes available.

SECTION III

RIDE QUALITY EVALUATION TECHNIQUE DESCRIPTION

1. ANALYSIS APPROACH

Reference 54 presented the basic mathematical methods for evaluating ride quality on the basis of human subjective discomfort. ASD-TR-68-18 (Reference 46) incorporated this mathematical method into a more complete ride quality analysis approach for crew discomfort. As Grande (Reference 54) suggested, the same analysis methods can be used in evaluating ride quality on the basis of performance error. In such a case, the frequency response function for human discomfort is replaced by a constant performance error frequency response function. The resulting output power spectrum and its associated σ^2 value can then be seen as a performance error power spectral density function and its mean square performance error respectively.

2. DEVELOPMENT OF METHOD

The sensitivity of an aircraft to gusts ($\bar{A}$) is expressed in the form of rms acceleration per unit of rms gust velocity. To allow for aircraft flexibility effects, the continuous nature of turbulence and the variation of gust power with frequency, the aircraft gust sensitivity must be calculated using power spectral analysis methods. The basic equation of the rms gust response caused by turbulence is

$$\bar{A} = \frac{1}{\sigma_u} \left[\int_0^{\infty} \left| T_{a/p}(f) \right|^2 \Phi_u(f)\, df \right]^{1/2}$$

$\Phi_u(f)$ is the gust power spectrum and $T_{a/p}(f)$ is the frequency response function for acceleration due to gust for a given reference fuselage station. For military aircraft ride quality purposes, the reference fuselage stations would normally be the crew station location. $\bar{A}$ represents the overall rms acceleration response in a broadband and random vibration environment.

The previous studies of vibration effects on humans have shown that task performance such as tracking error is not only a function of acceleration intensity but is also affected by the frequency of the vibration. Figures 21 and 24 as developed represent the threshold of constant error as a function of frequency, and can be thought of as the rms acceleration per unit tracking error. The inverse would be the relative error per rms g, and can be used as a frequency response function in power spectral density techniques to determine a measure of crew performance for any aircraft. The relationship used is an extension of the equation for aircraft gust sensitivity as follows:

$$\bar{H}_e = \frac{\sigma_e}{\sigma_u} \frac{1}{\sigma_u} \left[\int_0^{\infty} \left| T_e(f) \right|^2 \left| T_{a/p}(f) \right|^2 \Phi_u(f)\, df \right]^{1/2}$$

σ_e is the root mean square of the pilot tracking error response and $\bar{H}_e$ could be called the pilot tracking performance index, or in more general terms, the rms crew task error response and crew task performance index respectively for any given task such as tracking in the present case.

The normalized tracking error frequency response functions for vertical and lateral vibration are presented in Figure 25.

Tolerance curves based on discomfort normally vary in shape as a function of vibration intensity. Tolerance differences among frequencies become more sharply defined as the acceleration levels reach the objectionable levels. However, Magid and Coermann found that the curvilinearity of tolerance profile was also increased when duration of exposure to vibration was lengthened. Sufficient data to evaluate the exact effects of acceleration intensity or vibration exposure time on the shaping of the derived performance transfer function is not presently available. Since variability is characteristic of men and in consideration of the fact that the highest possible intensities were used in the derivation of the performance curves of Figures 21 and 24, it is believed that Figure 25 presents acceptable transfer function shapes without the need for detailed deviation due to exposure time or acceleration intensity.

SECTION IV

EXPOSURE-TIME CONSIDERATIONS

1. DATA REVIEW

An additional study was started to determine the general shape of an exposure-time curve as a function of rms error response σ_e for a constant performance error. Various experimenters have presented results regarding the effect of vibration exposure time on performance. As is the case for most of the parameters in vibration experiments on humans, the test results in this area are also limited and diffuse. Some data is for insufficient time length to indicate trends, other data is for different types of performance parameters or vibration conditions.

Generally, however, the tracking performance decreases rapidly in the initial stages of exposure time, it then tends to level off and possibly improve. In this study, the performance error at any time during the vibration exposure was written as a ratio to the pre-vibration static error measured in the experiment. Admittedly the static error changes with task duration. However, for simplicity and because static error data as a function of task duration was not always available, the pre-vibration static error was used as a base. Figure 26-33 present the tracking error as a function of vibration exposure time for various experiments. These figures also show the acceleration intensity values used in obtaining the data points of the experiments as well as the calculated values of the root mean square tracking error σ_e. The value of σ_e in each case was calculated using the frequency response functions as derived previously and as shown in Figure 25. In some cases the data points reveal considerable scatter which would tend to reduce confidence in their use. Section II of the study discussed the fact that there does not seem to be a single continuous variation of error with vibration amplitude, but rather that a break occurred which was assumed to be caused by involuntary muscular tensing. It was considered reasonable that this break would not only be a function of vibration amplitude but might vary during exposure. Correspondingly, the data where possible were examined in this light.

Indeed this examination resulted in the conclusion that this break changes with exposure time or trial, although not in any predictable manner, and that these changes are related to much of the scatter in the data.

Empirical curves were fitted judiciously to what were considered to be equal effect data points in those cases where this information was available.

2. DETERMINATION OF EXPOSURE-TIME RMS TRACKING-ERROR RESPONSE VARIATION

Initially it is assumed that at a given vibration exposure time, the value of the vibration error to pre-vibration error ratio varies as a function of rms error response or σ_e. The quality of this assumption can be evaluated from the basic data plotted in Figures 26 to 33. Examination of these figures will show that for each experimental data group, the ratio of the relative tracking errors for different values of σ_e is quite constant over the time of exposure. The test conditions represented by these plots are sufficiently varied to give credit to the conclusion that the assumption appears valid.

It is now possible to treat the exposure time data in a manner similar to that used in the derivation of the tracking error frequency response function. First the data is replotted in Figures 34, 35, and 36 in terms of constant error against exposure time and σ_e. To obtain a more complete view of the time-error interaction, the data was replotted for at least two constant error cuts for each experiment.

Examination of the replotted results indicates that the slopes appear to be relatively consistent; in all cases allowable exposure time decreases rapidly with increasing σ_e. At the lower exposure times, this rate is reduced slightly.

Since the error is considered a function of σ_e at constant time, the curves of Figures 34, 35, and 36 are now combined through the normalization procedure used previously. This procedure can be applied to each figure individually; however, it was found that the differences between the resulting curves were small. In view of the variability in the results of experiments involving human performance, it was decided that combination of the data would be justified. The final points are plotted in Figure 37 together with an empirically fitted curve.

This figure presents the results after a normalization of the data. The data points show that regardless of error type or direction of vibration, the general shape is quite consistent. It should be emphasized that this curve is the result of an attempt to determine the shape or slope of an exposure time curve which can be expected for constant error. It does not mean that the magnitudes of the different error types are identical. Neither is there any implication that the empirically fitted curve drawn through the data points represents a maximum allowable error level. If and when such a level is selected, exceeding the curve will mean exceeding the allowable error. Conversely, any point below the curve will mean errors less than maximum acceptable.

Having determined the shapes of the human performance curves and the exposure-time curves, it remains to consider the characteristics of the vibration environment, the level of the exposure curve, and the derivation of realistic design criteria.

SECTION V

AIRCRAFT VIBRATION ENVIRONMENT CONSIDERATIONS

The vibration to which a crew member is exposed during LAHS flight is the result of the aircraft response to atmospheric turbulence and the maneuvers required for terrain following. The accelerations resulting from aircraft response to turbulence are mostly a function of factors peculiar to a given aircraft configuration. Factors such as rigid body natural frequency, aerodynamic damping, structured stiffness and dynamics as well as the flight control characteristics have a powerful influence on the accelerations and their frequency distribution. The maneuver response on the other hand is more dependent on terrain type, terrain clearance requirements, terrain following system, etc., which are factors more common to any aircraft and rather less affected by configuration.

Because of the differences in the cause-effect relationship for turbulence and maneuver inputs, it seems reasonable to approach these two areas separately.

There is little doubt that the main portion of the tracking error for terrain following considerations is a function of terrain type and clearance requirements. These factors are usually dictated by mission requirements independent of the airframe design. This is not to say that the error cannot be held to a minimum through careful design for gust sensitivity.

The tracking error increase over static vibration condition as a function of time is affected by intensity and $\overline{H}_e$.

For instance Figure 30 shows that for flat terrain, the pitch error increase after 2 hours is 28.5% for $\overline{H}_e = .111$ and 48.5% for $\overline{H}_e = .222$. In mountainous terrain, these differences are 10 and 37% respectively.

Human tolerance levels or tracking error levels are a function of rms vibration intensity, duration of exposure, and predominant frequency. Maneuver acceleration frequencies are predominantly around .1 to .7 Hertz. Due to lack of vibration studies which incorporate the pilot in the loop and the difficulty of simulating low frequencies to sufficiently high intensity values, little is known of the vibrational effects on tracking performance at such low frequencies during actual terrain following.

Also some LAHS flight studies indicate that a pilot will try to maintain a fairly constant intensity level. When the turbulence intensity increases his tracking performance will decrease, whereas during lesser turbulence levels, his terrain following effort will improve. The flexible motions due to surface motion required to fly over terrain will cause additional rms acceleration increases of from 4 to 1% of the gust contribution depending on terrain type.

Based on the above considerations, the conclusion of Reference 49 that the effects of turbulence with respect to human tolerance are more significant than the maneuvering loads seems still tenable. It was, therefore, decided to put the emphasis on crew efficiency factor as a function of aircraft gust input only.

SECTION VI

CRITERIA DEVELOPMENT

1. GENERAL

Using the tracking error frequency response function developed, the $\overline{H}_e$ values were calculated for a number of airplanes and airplane configurations. The gust spectrum used was the Von Karman spectrum with an $L = 500$. The results are presented in Table IV. As can be seen, the values of $\overline{A}$ and $\overline{H}_e$ vary considerably for each airplane depending on configuration, speed, or weight.

It would be desirable if information regarding maximum allowable error versus time and $\overline{H}_e$ were available or could be derived for these aircraft. Although considerable effort in this direction was expended during the study, the conclusion was that this approach was not the most productive one at this time. First, tracking error does not appear to be a measured quantity during LAHS flight tests.

Secondly, due to many differences, simulator tests provide neither consistent nor compatible results. Also, the results of simulator test although valuable in indicating error trends cannot be relied upon to provide actual numerical performance values consistent with a real airplane. In most studies, the tracking performance was evaluated in an open-loop system. Although it is not believed that this would affect the error significantly, it would no doubt alter the exact error values to some degree. In addition, the effect of the emotional tension associated with the possibility of a potential crash or fear for the structural integrity of the aircraft should not be dismissed lightly. It is exactly this effect which is lacking in any simulator study.

The determination of a definite numerical tracking error criteria would be highly desirable in light of the availability of a tracking performance transfer function derived earlier, but this does not appear feasible at this time.

An alternate approach is the evaluation of ride quality based on pilot comments during low-level flight. Admittedly, this approach involves the vagueness inherent in the subjective comment. However, it is expected that a pilot's evaluation of his effectiveness is based on his ability to perform

LAHS flight to acceptable levels. As is common in the whole area under discussion, very little information is available on crew response during low-level flying. Table V presents some general ride quality information collected from various sources. The calculated values of $\overline{H}_e$ are for the most part representative aircraft configurations based on a review of the aircraft mission and flight environment to which the comments are applicable.

Pilot evaluation of a turbulence level is related to the airplane response characteristics and, in turn, to the value of $\overline{H}_e$. The same review, therefore, provided the relationship between the pilot evaluation of turbulence severity and the measured gust velocities.

Note that the comments appear to be based on vertical vibration input and characteristics only. It appears that when the lateral vibration in terms of $\overline{H}_e$ is less than the vertical vibration the latter will govern the subjective evaluation. In other words, even though the lateral low-altitude gust environment is more severe and the lateral crew sensitivity greater than in the vertical direction, the lower lateral aircraft response characteristics make the vertical vibration environment the most bothersome. The relationship between the vertical and lateral tolerance criteria will be discussed further under 3 and 4.

2. VERTICAL VIBRATION CRITERIA

With the value of $\overline{H}_e$ known and the measured gust inputs identified, the crew exposure-time estimates can be obtained as a function of $\sigma_u \overline{H}_e$ as shown in Figure 38. Although the data points are few and for only three aircraft, the agreement with the shape of the derived exposure-time curve of Figure 37 is obvious.

Figure 38 does not, however, provide a tolerance curve which can be directly related to design requirements. Due to the random nature of turbulence, a probability of exceedance of any specified level must be included as part of any requirement.

This probability should be related to consideration of the effects resulting from exceedance of a given tolerance level. The total effects of exceeding long-time tolerance levels (say above 20 minutes) are not identical to those resulting from short-time tolerance level exceedances.

The long-time estimates are determined mostly by pilot performance of psychomotor tasks. Such tasks, which call for precise muscular coordination such as tracking, throwing switches, or using handhold navigational aids are more dependent on frequency effects and to a lesser extent on intensity. Exceeding these levels will result mainly in lesser performance effectiveness and long-time fatigue and discomfort. At the short time levels, performance of psychomotor tasks deteriorates very rapidly with small change in exposure time. These levels quickly produce extreme fatigue, high levels of unspecified stress and anxiety; and any exceedance affects aircraft safety through submarginal pilot control ability.

Table VI presents a brief description of some psysiological effects as derived from both simulator and actual flight tests. The information in this table is arranged in a manner similar to that used in the Cooper-Harper scales for the evaluation of aircraft handling qualities. The values of $\sigma_u \overline{H}_e$ are the maximums to which the comments apply.

When using this table in order to determine the point of separation in terms of $\sigma_u \overline{H}_e$ or σ_e between the long term and short term tolerance levels, it is important to use a conservative approach. The present state-of-the-art allows an aircraft design to be optimized to definite mission requirements to a much greater degree than previously. Supposedly, these postulated mission requirements are based on the best estimates and predictions of usage and tactics necessary for a successful strike capability. To select unconservative criteria on the basis that a pilot has the ability to improve ride through changes in speed, altitude, or wing sweep may well jeopardize successful mission completion.

Using the physiological effects and acceptance levels of Table VI as a guide, a maximum value of $\sigma_u \overline{H}_e = .25$ is selected as satisfactory for normal long-time operation. For short-term operation, a decrease in overall crew effectiveness is accepted on the assumption that the remaining tasks will be performed when acceptable conditions return. A minimum value of $\sigma_e = .25$ is selected for the short-time operation.

It is difficult to determine an acceptable probability of exceedance on an absolute basis for either the long-term or short-term levels. This can best be determined indirectly based on a qualitative comparison of the ride quality estimates of other aircraft. It is postulated that crew exposure-time estimates for a given effectiveness or discomfort level are influenced by the rate of exceedance of σ_e associated with a particular aircraft. This would be in agreement with the contention by Notess in Reference 18 that a factor which causes significant differences in ride comfort is the rapid change in the probability of encountering turbulence as the magnitude of the intensity decreases. It is considered that on the average the low-level flights for the aircraft were over identical terrain types and made under identical meteorological conditions. If this consideration is assumed to be correct, it becomes possible to evaluate an aircraft's overall ride quality estimate in terms of the basic exposure-time tolerance curve and the probability of exceedance.

Using the turbulence statistical parameters of Appendix I as representative of the average conditions, the probability of exceedance of the tolerance level of Figure 38 was determined for various aircraft. Figure 39 provides a graphical presentation of these probabilities as a function of $\sigma_u \overline{H}_e$. Cross plotting of Figures 38 and 39 provides the probability of exceedance of the tolerance boundary as a function of exposure time which might have occurred on these aircraft. Figure 40 presents this information with the data points obtained from Table V. For short duration or $\sigma_u \overline{H}_e$ values above approximately .25 the probability of exceedance appears of little importance. In this area we are mainly concerned with crew tolerance. The performance effectiveness is of secondary importance, and the exposure times are time estimates after the pilot must take action to reduce the value of $\sigma_u \overline{H}_e$ by changing speed or altitude or both in order to be able to continue the mission.

At the lower $\sigma_u \overline{H}_e$ values, there does indeed appear to be a relationship between exposure time and probability of exceedance. Reevaluating the information of Table V in this light, it can be said that for a given exposure time and probability of encounter, the aircraft's ride quality is directly related to its $\overline{H}_e$ value.

Finally considering the information presented in Table V and Figure 40, the following preliminary criteria are proposed for design purposes.

a. The probability of exceedance for long-time exposure shall not be greater than 20%.

b. For short-time exposure tolerance, the probability of exceedance of the exposure-time curve shall not be greater than 1%.

3. LATERAL VIBRATION CRITERIA

The direction of vibration is of much importance. It has been stated that low-frequency lateral vibration is less tolerable than vertical vibration of the same intensity. Guignard (Reference 41) discusses some work by Loach who derived a factor of $\sqrt{2}$ for threshold differences between the lateral and vertical vibration. Lateral vibration is equated in discomfort with a vertical vibration at acceleration levels of $1/\sqrt{2}$ times the vertical acceleration. Notess references experiments which show that equivalent tolerance boundaries or comfort ratings are obtained when rms lateral vibration is lower than the rms vertical vibration by factors ranging from 1.4 to 2.0. It is obvious from a comparison of the quite different shapes of the performance curves for vertical and lateral vibration that such general statements do not allow a direct application in order to determine the relative performance curve levels for lateral and vertical vibration. Our studies of References 28, 52, and 53 which present lateral and vertical tolerance curves resulted in the determination that when placing the lateral tolerance or tracking error curve to go through an acceleration value of .425 times the vertical acceleration at the anchor point of 1 Hertz, the best compromise over the frequency band of interest is obtained. This would mean that the frequency response curve for lateral vibration would go through a point $1/.42 \approx 2.40$ times the vertical point at 1 Hertz.

Additional considerations tend to confirm this relationship. For instance, References 51 and 27 present horizontal tracking data for a vertical and a lateral vibration study respectively. The experiments are quite similar and the same vibration facility was used. Rationing the rms acceleration of an identical error for the vertical and lateral cases at frequencies and amplitudes where identical muscular tensing was suspected supports the relative levels based on equal comfort as discussed above.

Until more detailed data becomes available for tests which incorporate vertical vibration and lateral vibration under identical task loadings, the relationship between the frequency response functions as presented in Figure 41 is considered the best compromise.

Reevaluating the $\overline{H}_e$ values for the lateral case for the aircraft of Table IV results in the $\overline{H}_e$ values of column 12. Note that the lateral rms error response sensitivity index is lower than the vertical index values. As mentioned previously, this is very likely the reason why the lateral vibration environment has apparently not been a problem in military aircraft to date.

The methods described in Section III are based on the assumption that identical rms error response values, σ_e, result in identical errors at the same exposure time providing that the proper relationship between the vertical and lateral frequency response curves is established and that a "universal" design exposure time curve is available.

The exposure-time curve of Figure 38 is based on vertical vibration inputs only. Before a decision can be made regarding the use of this curve as a design curve for both vertical and lateral vibration, it is important that the vertical to lateral relationship be understood in terms of a combined-axis vibration environment.

4. COMBINED-AXIS VIBRATION CRITERIA

Most vibration experiments to determine tolerance levels have been carried out separately for the vertical and lateral directions. Those experiments which were used to determine crew performance during LAHS flight conditions tried to incorporate representative aircraft response characteristics with their inherently lower lateral responses.

Reference 52 draft states that if vibrations occur in more than one direction simultaneously, the corresponding limits apply separately to each component. This statement incorporates the idea that the vertical and lateral tolerance levels are independent of each other. Data from References 53 and 61 however, would seem to refute this fact. Figure 42 shows this data in terms of rms tracking error for simultaneous vertical and lateral vibration. The rms tracking error response values were determined using the performance frequency response functions of Figure 41. From the data points of Figure 42, it can be concluded that the total tolerance value for σ_e is based on a constant vector sum of σ_{e_V} and σ_{e_L}. There is, of course, always the question of whether this conclusion is correct under all circumstances, and combinations of vertical and lateral vibration for purposes of crew effectiveness. Figure 43, presents the variation of $\overline{H}_{e_V}$ and $\overline{H}_{e_L}$ for the airplane configurations of Table IV. It will be noted that the average lateral response is approximately half the vertical, and that the boundaries b and c which are based on $\overline{H}_{e_{L_{b,c}}} = (\overline{H}_{e_L})_a \pm .5(\overline{H}_{e_L})_a$ for any given $\overline{H}_{e_V}$ will include most points. The exposure-time curve of Figure 38, although based on a vertical vibration input only, does, of course, include some lateral influences. Exactly how much is impossible to determine from the available data. Until more data becomes available, it is proposed that the rms vertical error response from Figure 38 be considered applicable to the average $\overline{H}_{e_V}$ versus $\overline{H}_{e_L}$ line of Figure 43. In general then, the following steps are proposed to determine design requirements:

(1) Determine the allowable σ_{e_V} for the correct exposure time from Figure 38.

(2) Divide the allowable σ_{e_V} by any appropriate rms gust velocity (20% probability of exceedance has been proposed for long term).

(3) Plot this point on line a of Figure 43. This will determine the allowable vector sum of $\overline{H}_{e_V}$ and $\overline{H}_{e_L}$.

(4) Allow the value of $\overline{H}_{e_V}$ and $\overline{H}_{e_L}$ to vary within the boundaries of lines b and c, keeping the vector sum constant.

It is expected that this approach will result in ride quality relationships for the vertical and lateral case which are not significantly different from that on present aircraft. It is to be hoped that more information on the interaction between vertical and lateral vibration becomes available. As the state-of-the-art in ride quality design advances, it may then become possible to allow significant tradeoffs to be made in the ride quality requirements for different directions.

SECTION VII

CONCLUSIONS

The intent of the studies was to try to determine ride quality criteria based on exact numerical crew performance effectiveness values. This was not accomplished. The design criteria as proposed does not result in a clearly defined quantitative crew performance effectiveness. It is rather a qualitative approach based on empirical information which is expected to result in a satisfactory level of ride quality.

Although differences of opinion regarding assumptions and evaluation of the referenced data must be expected, the procedures and final design criteria are considered the most practical at this time from an engineering viewpoint. It should not be forgotten that the large variability between individuals or even between the same individual at different times will overshadow any lack of precision which might be present in most assumptions. In addition, neither the exact magnitude of the required performance nor the acceptable probability of exceedance of any performance parameter has ever been established.

The tracking error frequency response functions as derived are based on vibration experiments using sinusoidal inputs, but this is no different from the approach used to determine airplane vibration frequency response functions. Furthermore, the approach as developed is based on the relative vibrational influences between vertical and lateral vibration and the relative crew performance responses between different aircraft. If there are differences in quantitative rms performance response levels or even discomfort levels between sinusoidal and multiple frequency or random vibration inputs, and some experiments (e. g. , References 1 and 53) do not support this contention, the relative relationships would still be valid.

There are, of course, the effects of seat dynamics and restraint systems which were not directly considered in the evaluation of the pilot estimates while using the derived frequency response functions. A good restraint system would improve crew performance and comfort. Its effects are implicit in the crew comments. The effects of the seat dynamics were impossible to evaluate due to lack of knowledge of these characteristics for the airplanes involved.

Finally, we have thought in terms of pilot effectiveness and tracking performance. Much additional work needs to be done to define pilot performance as influenced by conditions of automatic terrain following as well as the effectiveness of other crew members.

Regarding the use of an automatic terrain following system, such a system can generally achieve lower average heights above ground level than the pilot. This is at the cost of higher rms g intensities.

Regarding the other crew members, it is reasonable to assume that the shape of the human performance curve as derived is representative of most psychomotor tasks. Until further information becomes available, it is believed that the criteria as suggested can be considered applicable (though less conservative than for the pilot) to general crew effectiveness evaluations and design requirements. This is so in particular because the pilot has the opportunity to anticipate terrain following maneuver acceleration and possible turbulence patches based on his view of the outside environment.

TABLE I

VIBRATION INTENSITIES FOR CONSTANT RELATIVE ERROR

			Frequency — Hz																								
			75	.9	1.0	1 5	2 5	3.0	3.5	4 0	4 5	5 0	5.5	6 0	6 5	7 0	8 0	9 0	10	11	12	13	14	15	18	24	27	σ_n/σ_m
1	▽	σ			.2													.265	.34			.57	[illegible]		1.0		1.33	σ_1/σ_1
		R			1														1				1		1			
2	□	σ														12	.18	.20			.35	.43	.48		.38	1.08		σ_1/σ_2
		R																1 35				1.32	1.35		1.28			
3	△	σ								.29	.34	.40			.59	.66	.82			1.6	1.9	2 3						σ_2/σ_3
		R														.182	.195				.189	.187						
4	○	σ								.09	.11	.12	.135		.16	.17	.24			.42	.58							σ_3/σ_4
		R								3.12	3.08	3 33			3 69	3 88	3 59			3 3	3 19							
5	▽	σ			.21														.36				.73					σ_1/σ_5
		R			95														.945				89					
6	◇	σ		.13			.18	165	.15			087	.097															σ_6/σ_9
		R		1 24			1 09	97	885				1 29															
7	◇	σ									.20		22		.35													σ_4/σ_7
		R									.55				64													
8	▯	σ					.136	102	.085																			σ_6/σ_8
		R					132		1.85																			
9	▽	σ		16	.19	.33	195	.165	135				125	.14					.28									σ_1/σ_9
		R			1.05														1 21									
10	▽	σ			.23			.215						.19					.34				.64		.96			σ_9/σ_{10}
		R			87														1 0				1 01		1 16			
11	◺	σ								.16				.26			.39			.97				1.75				σ_4/σ_{11}
		R								.58							.615			51								

TABLE II

NORMALIZATION CONSTANTS K

		$1/\sigma_1$	σ_1/σ_2	σ_2/σ_3	σ_3/σ_4	σ_1/σ_5	σ_4/σ_7	σ_4/σ_{11}	σ_1/σ_9	σ_1/σ_{10}	σ_6/σ_9	σ_6/σ_8	K
1	▽	1											5
2	□		1.33										6.65
3	△			1.88									1.25
4	○				3.44								4.3
5	▽					.928							4.65
6	◇										1.1		6.25
7	◇						5.95						2.56
8	▯											1.56	9.75
9	▽								1.13				5.65
10	▽									1.01			5.05
11	◺							.575					2.47

TABLE III

NORMALIZED CONSTANT ERROR VIBRATION INTENSITY VALUES

	Frequency – Hz																								
	75	9	10	15	25	30	35	40	45	50	55	60	65	70	8.0	90	10	11	12	13	14	15	18	24	27
▽			1.0														1.7				3.25		50		6.7
□															107					286			5.2	7.0	
△								365						.83					2.38						
○										.52				.73				2.1							
▽			98														167				3.38				
◇		81			113		.94				.61														
◇									.512				.64												
▯					133		.81																		
▽			108	1925		91						.79					16								
▽			116			109						9.6					1.73				3.23		435		
◺								395				642			.964			24				4.32			

TABLE IV

RIDE QUALITY COMPARISON

1	2	3	4	5	6	7	8	9	10	11	12
Acft	Mach No	G.W.	Altitude	Λ	Fus Sta	$\bar{A}v$	$\bar{H}_{e_v}$	Fus Sta	$\bar{A}_L$	$\bar{H}_{e_L}$	$\bar{H}_{e_L}$
F-111A	.6	66710	S.L.	26°	P.S.	.0385	0458		N/A		
"	.6	90350	"	26°	"	.0234	.0308				
"	.9	66710	"	50°	"	.0409	.0484				
"	1.2	66710	"	72.5°	"	.026	.0245				
FB-111	.8	48300	S.L.	26°	P.S.	.0532	.0526	P.S.	.00811	.0039	.0094
"	.8	84300	"	26°	"	.0294	.0288	"	.00568	.0030	.0072
"	9	48300	"	50°	"	.0320	.0327	"	.0145	.0055	.0132
"	.9	84300	"	50°	"	.0216	.0203	"	.0115	.0051	.0122
"	.9	48300	"	72.5°	"	.0296	.0264	"	.0144	.0078	.0187
"	9	84300	"	72.5°	"	.0158	.0192	"	.0135	0060	.0144
B-52H	.435	350000	2000'	N/A	P.S.	.0217	.0293	P.S.	.0087	.0054	0130
"	.6	350000	"	"	"	.0378	.0495	"	0114	.0068	.0163
"	.6	450000	"	"	"	0329	.0437	"	0137	.0088	.0211
"	.435	450000	"	"	"	.0202	.0285	"	.0084	.0052	.0125
"	.6	220000	"	"	"	.0458	.0604	"	.0199	.0123	.0295
"	.435	220000	"	"	"	.0306	.0419	"	.0076	.0048	.0115
"	.6	270000	"	"	"	.0429	.0557	"	.0204	.0127	.0305
"	.435	270000	"	"	"	.0266	.0365	"	.0082	.0051	.0122
B-58	.92	132200	2000'	N/A	P.S.	.0285	.0331	C.G.	.009	.0076	.0182
"	.92	92100	"	"	"	.0312	.0377	"	.0161	.0147	.0353
"	.80	134700	"	"	"	.0297	.0359	"	.0066	.0054	.0130
"	.80	95000	"	"	"	.0304	.0401	"	.0103	.0092	.0221
"	.79	161000	"	"	"	.0229	.0260	"	.0081	.0070	.0168
"	65	140000	"	"	"	.0223	.0319	"	.0051	.0042	.0101
B-66	.516	64700	3320'	N/A	C.G.	.0273	.0395		N/A		
"	.755	61600	3528	"	"	.0476	.0591				
F-105	.937	34350	1570'	"	C.G.	.040	.049		N/A		
"	.953	36360	580	"	"	.058	.078				

TABLE V

GENERAL PILOT EFFECTIVENESS COMMENTS

A/C	$\overline{H}_{e_v}$	General Pilot Comments
F-111A Λ 72.5°	.0245	Ride Better than B-58
B-58	.034	No problem flying contour for 120 minutes while average gust velocity 4 fps rms. Ride better than F-111 @ Λ = 50°.
B-66	.0395	Difficult to recommend flights of more than 120 minutes in light turbulence levels (3 fps). In moderate turbulence (4.25 fps) fatigue increased an estimated 100%. All of pilot's and flight engineer's attention is demanded. Hazardous during heavy turbulence (7 fps). ten to fifteen minutes duration considered critical.
B-52H	.043	Ride much rougher @ Mach 0.6 than B-58 @ Mach 0.9.
F-111 Λ 50°	.0485	Ride worse than B-58.
F-105	.0495	Average estimates of pilot effectiveness ranged from 9 minutes during severe turbulence (5.6 fps) to 40 minutes for moderate turbulence (3.85 fps). Major fatigue due to extreme concentration, anxiety, and manual tasks. Instrument reading difficult after 15 to 30 minutes of flight.

TABLE VI

CREW-MISSION PERFORMANCE LIMITATIONS

$\sigma_u \overline{H}_e$	Aircraft Acceptability	Mission Performance & Crew Effort	Physiological Effects
.07	Acceptable for unlimited exposure time.	Mission performance not affected.	No effect on normal tasks.
.14	Acceptable normal operation.	Mission performance adequate.	No effect on normal tasks, writing becomes difficult, small dials become difficult to read.
.21	Acceptable normal operation not exceeding allowable exposure time.	Adequate for mission success; reasonable performance requires considerable crew concentration.	Normal tasks still possible. Manual control demands considerable attention and psychomotor coordination is reduced. Time to read instruments and displays and adjust controls increases. Small dials unreadable. Eventual setting in of fatigue.
.28	Unsatisfactory for normal operations; unacceptable when exceeding allowable exposure times.	Adequate for mission success, but requires max. available pilot/crew concentration to achieve acceptable performance.	Limits of effective tracking. Manipulation of controls and other psychomotor tasks requires bracing of arms and legs and movements become deliberate. Pilot looks forward with only brief glances at instruments which cannot be read accurately. Cross checks are slowed down and tolerances widened. Rapid increase in fatigue.
.35	Unacceptable except for emergency conditions.	Inadequate performance for mission success; aircraft controllable with minimum cockpit duties.	Beginning of unworkable level. Control of aircraft requires full pilot attention. Tasks other than stick and throttle control almost impossible. Pilot will establish hierarchy of tasks. Attention cannot be diverted from tracking task without immediate deterioration.
.42	Unacceptable, dangerous.	Aircraft just controllable requiring max. pilot skill; mission success impaired.	Performance levels low and all tasks impossible except for gross adjustments. Displays difficult if not impossible to read. Concern for structural integrity.

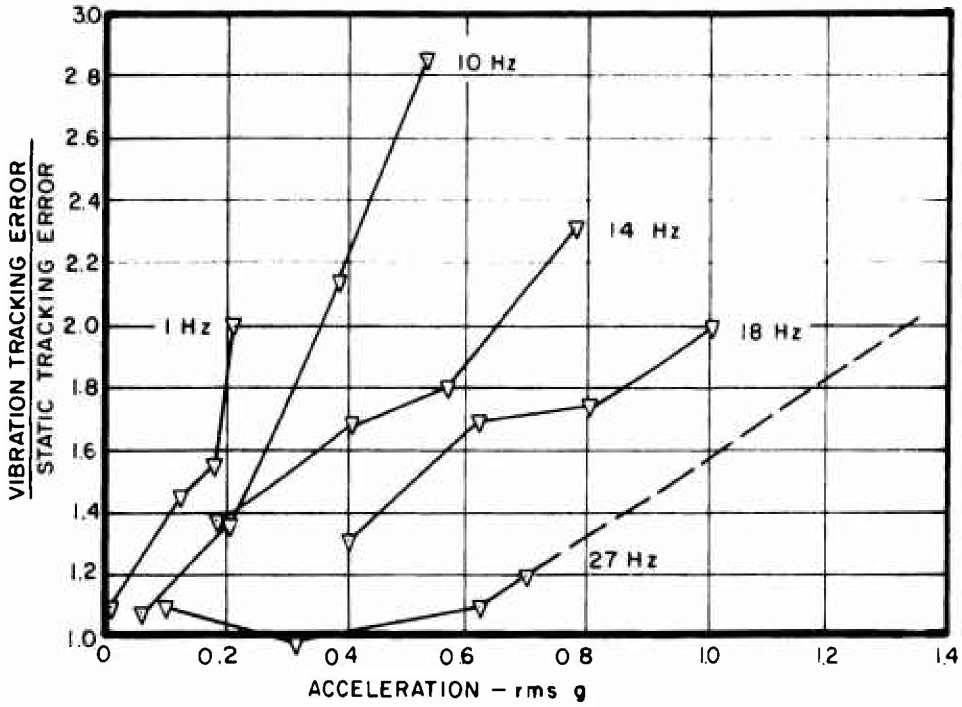


Figure 1. Relative Vertical Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 35)

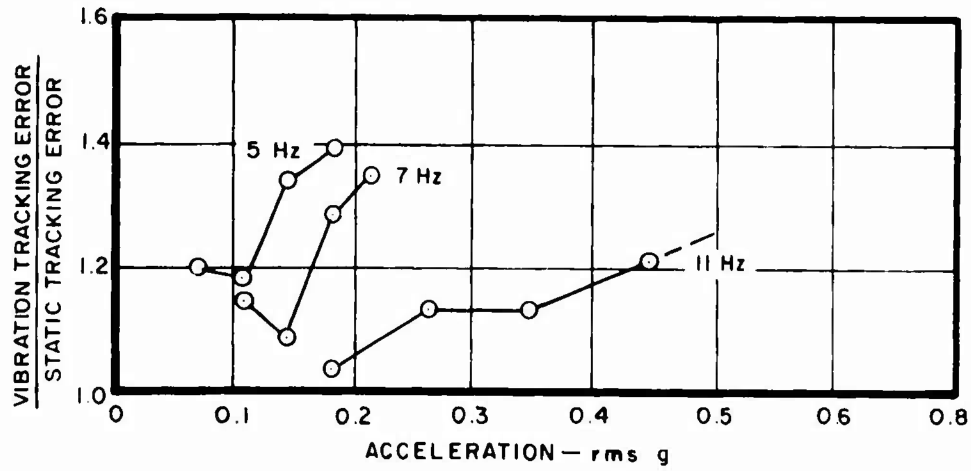


Figure 2. Relative Vertical Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 4)

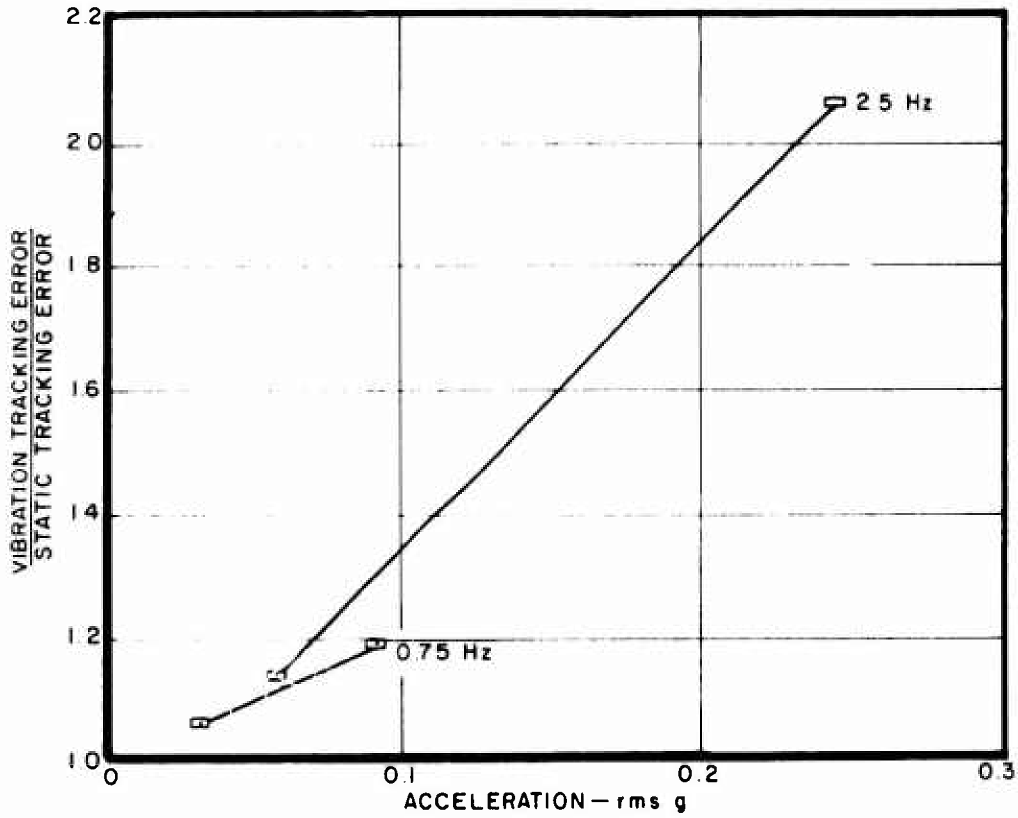


Figure 3. Relative Vertical Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 1)

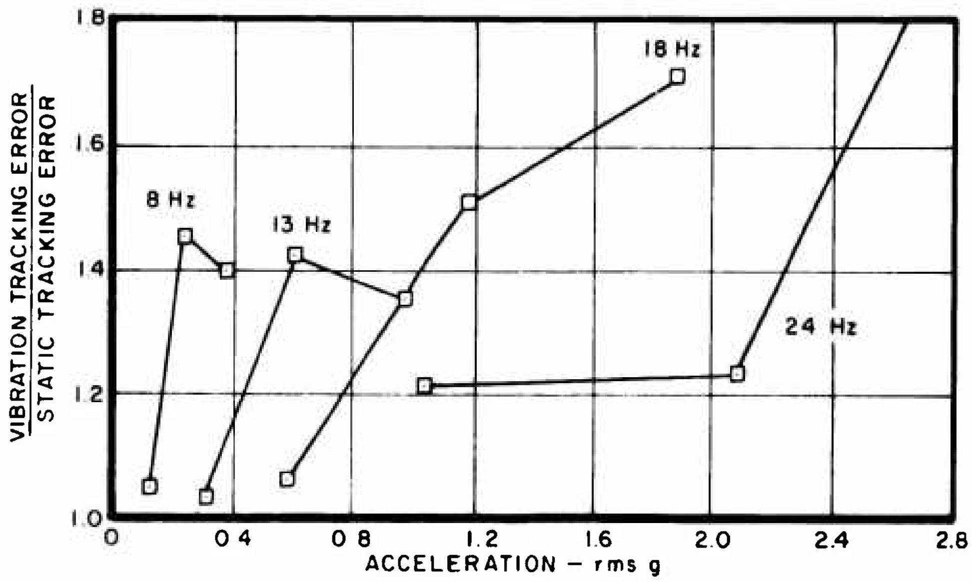


Figure 4. Relative Vertical Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 36)

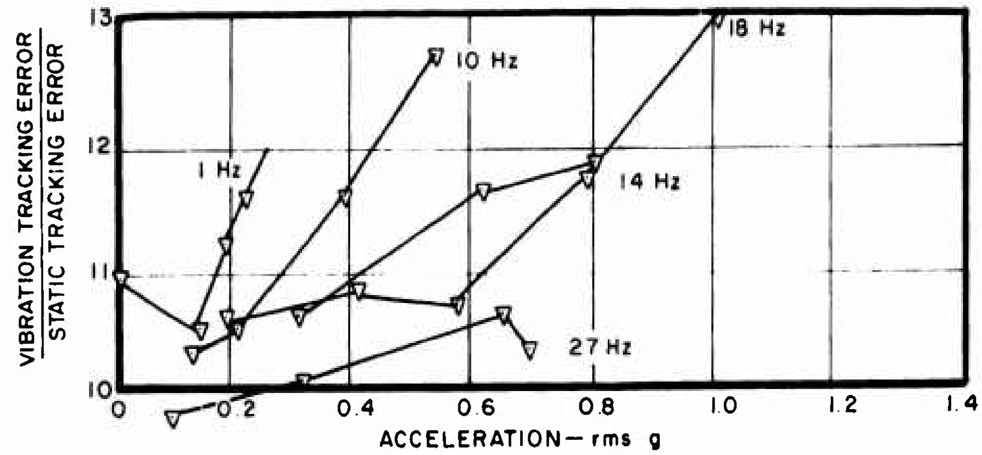


Figure 5. Relative Horizontal Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 35)

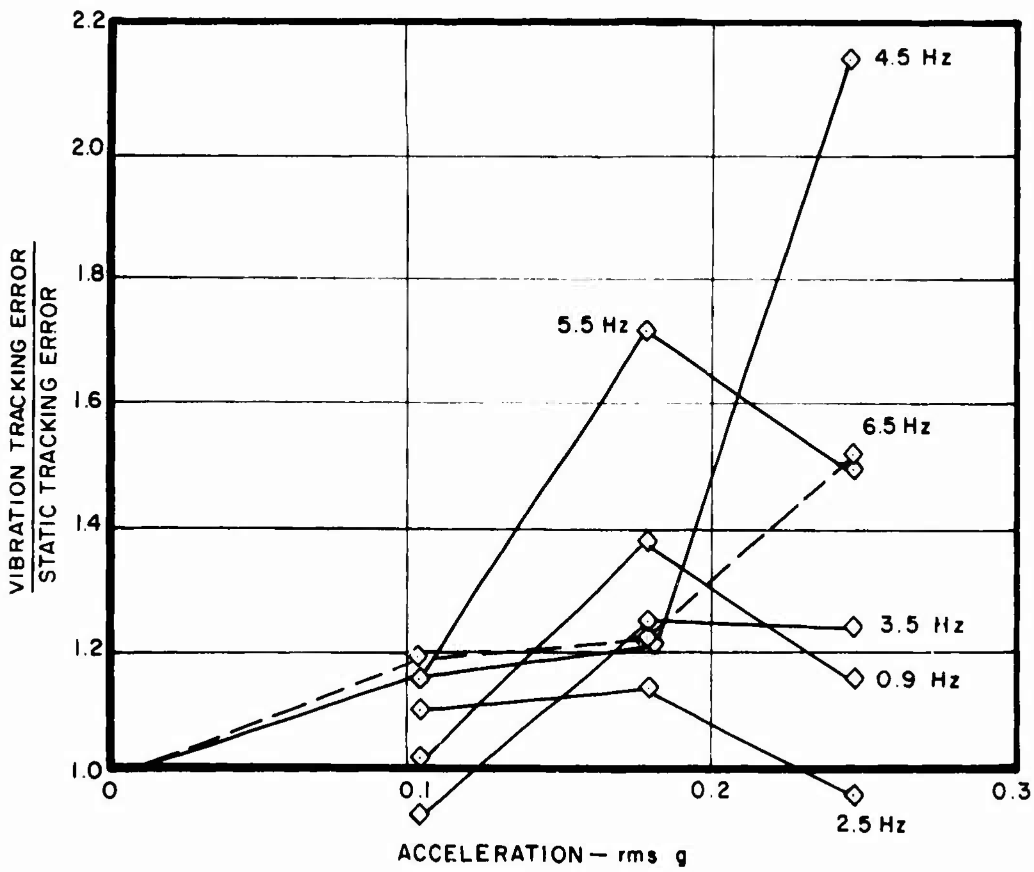


Figure 6. Relative Horizontal Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 51)

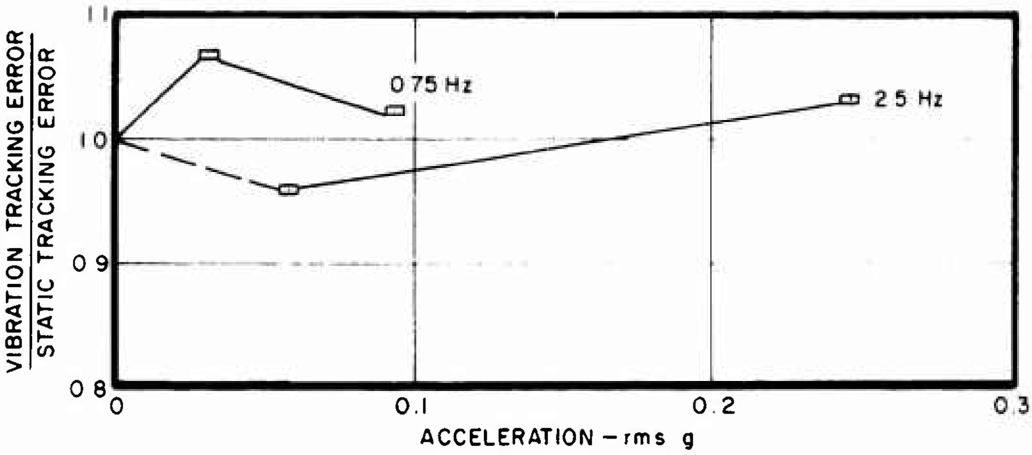


Figure 7. Relative Horizontal Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 1)

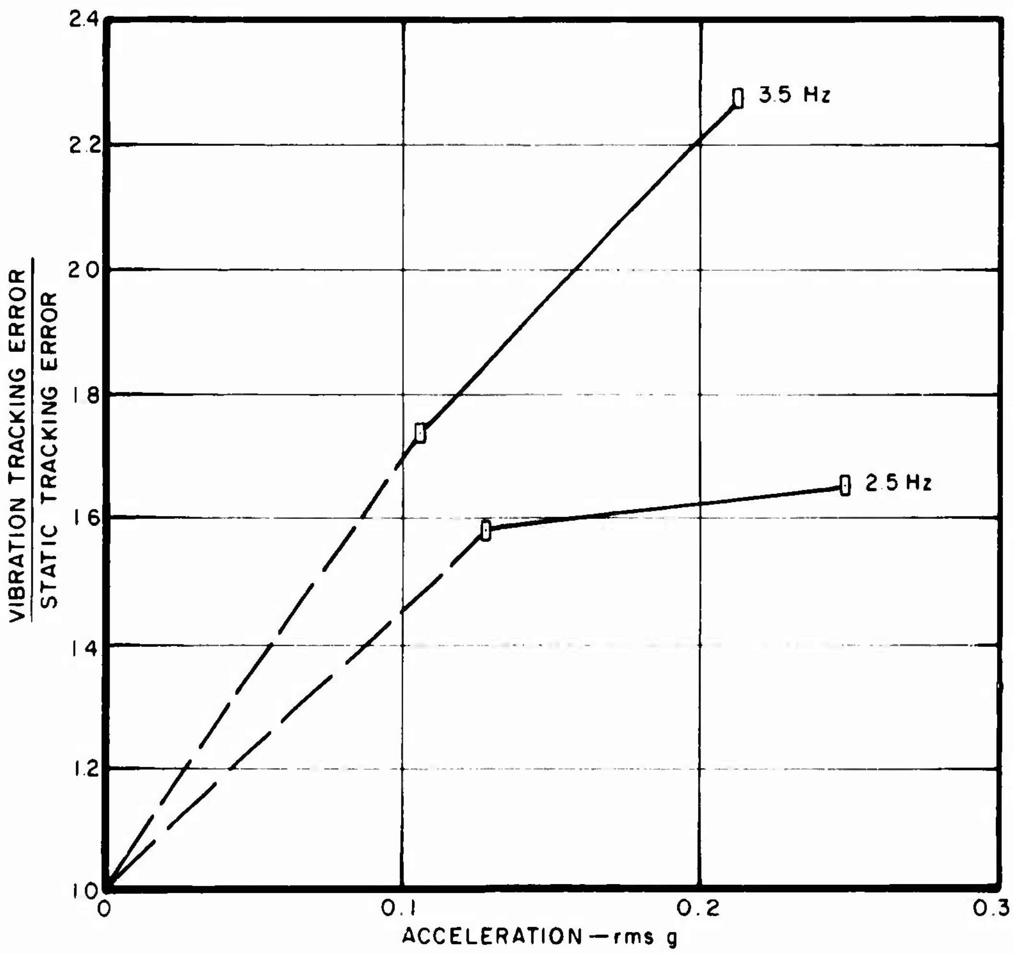


Figure 8. Relative Horizontal Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 38, 51)

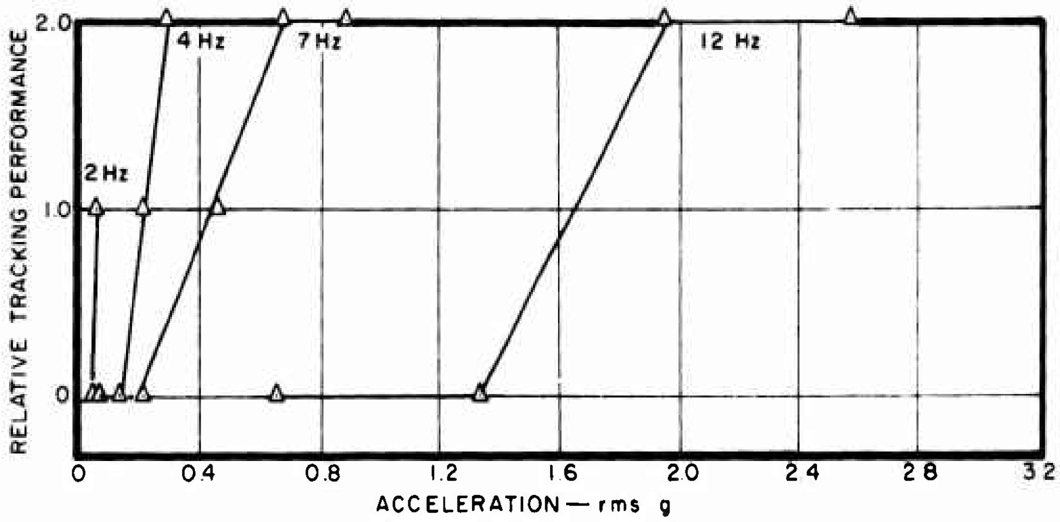


Figure 9. Relative Total Tracking Performance as a Function of Vertical Vibration Intensity and Frequency (Ref 34)

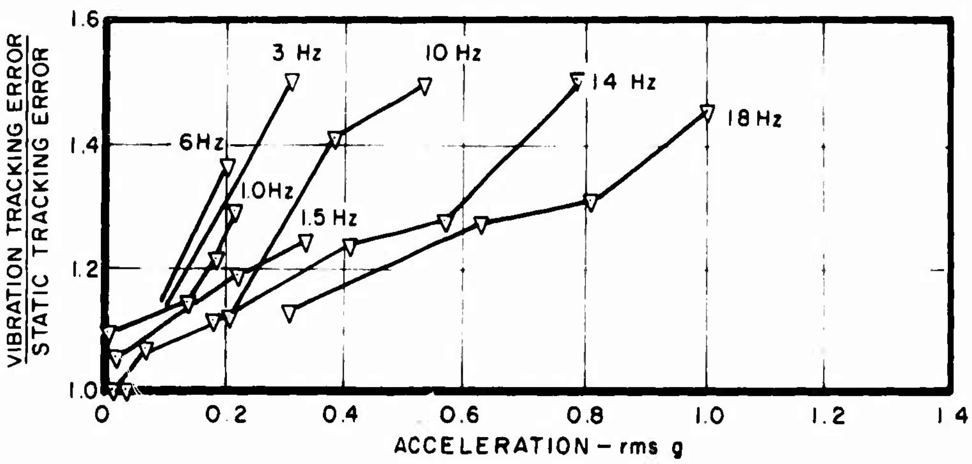


Figure 10. Relative Total Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 35)

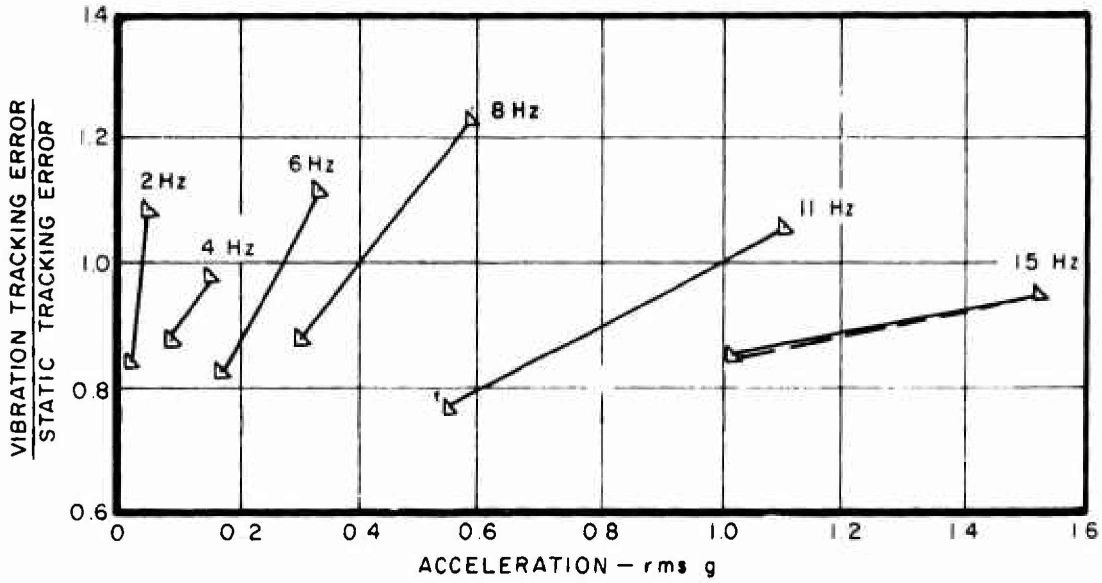


Figure 11. Relative Total Tracking Error as a Function of Vertical Vibration Intensity and Frequency (Ref 29)

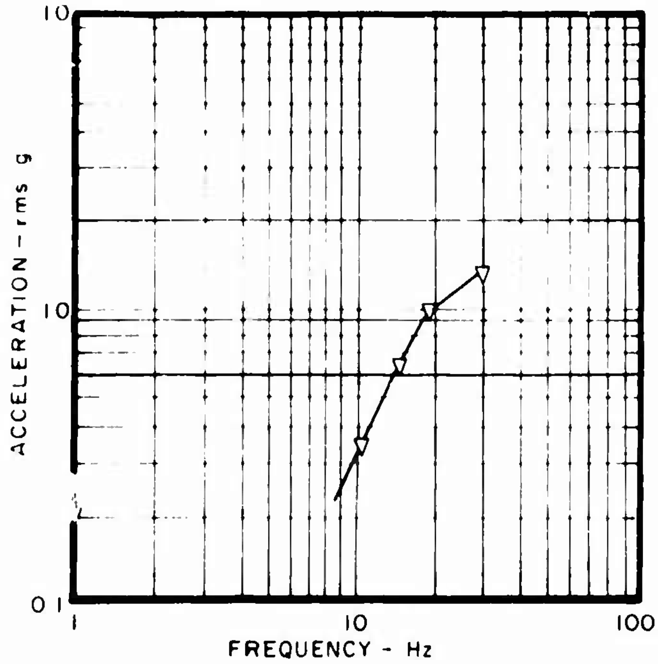


Figure 12. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Vertical Error (Ref 35)

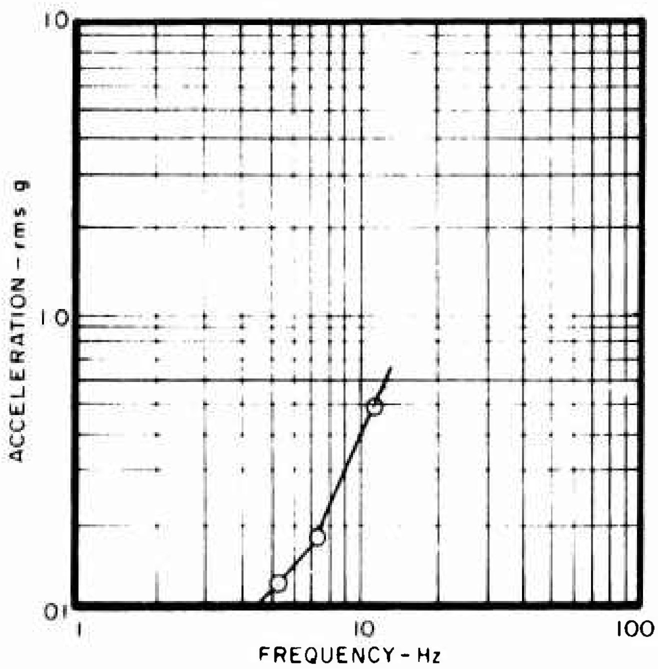


Figure 13. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Vertical Error (Ref 4)

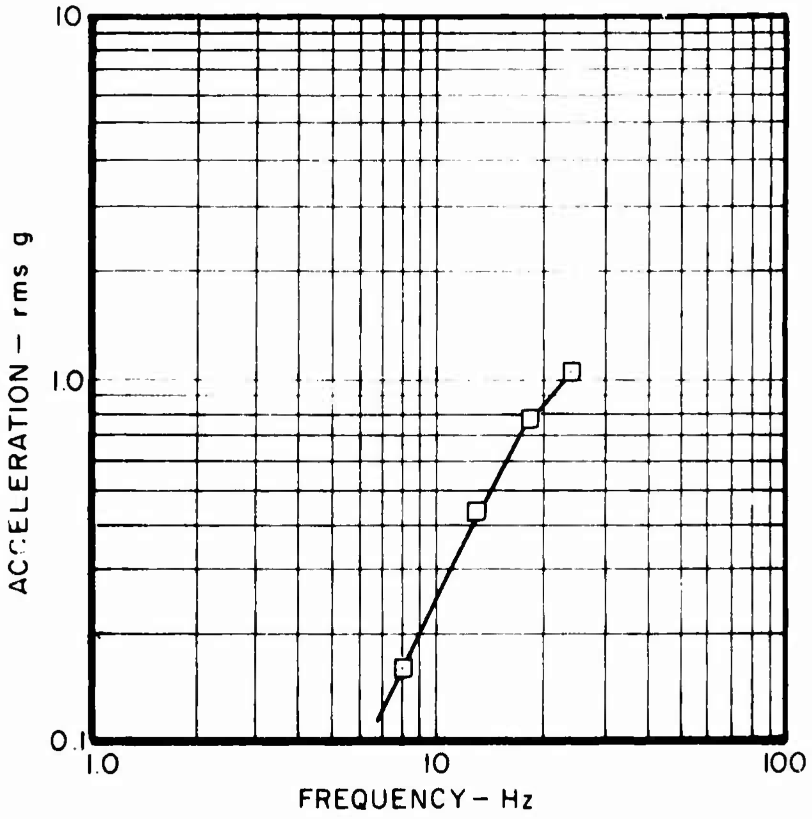


Figure 14. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Vertical Error (Ref 36)

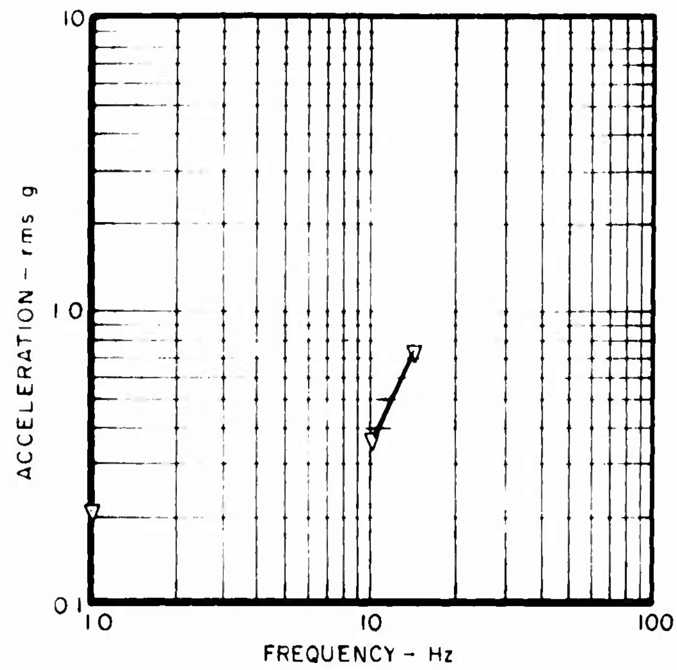


Figure 15. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Horizontal Error (Ref 35)

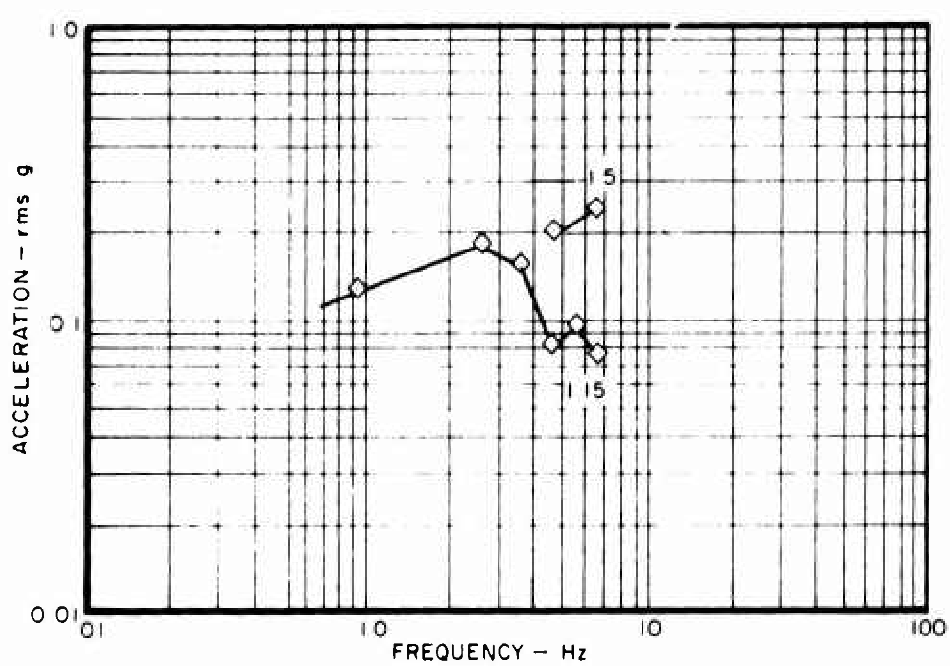


Figure 16. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Horizontal Error (Ref 51)

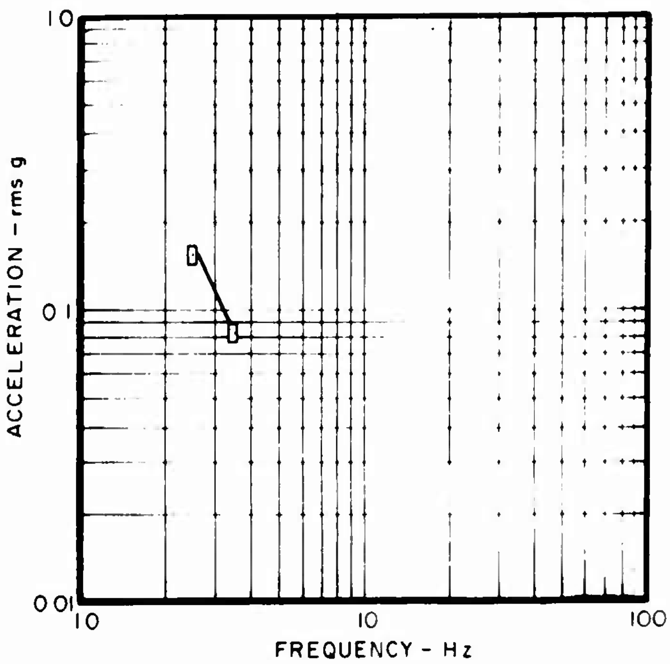


Figure 17. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Horizontal Error (Ref 38)

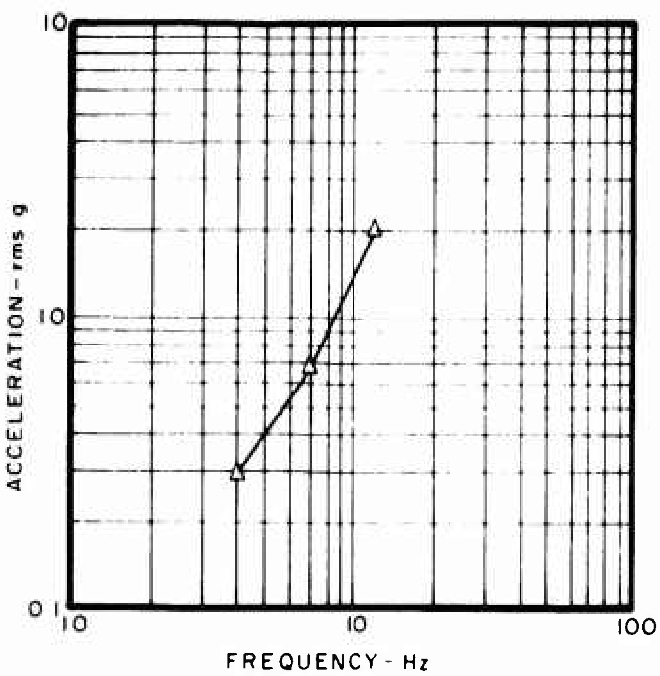


Figure 18. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Total Error (Ref 34)

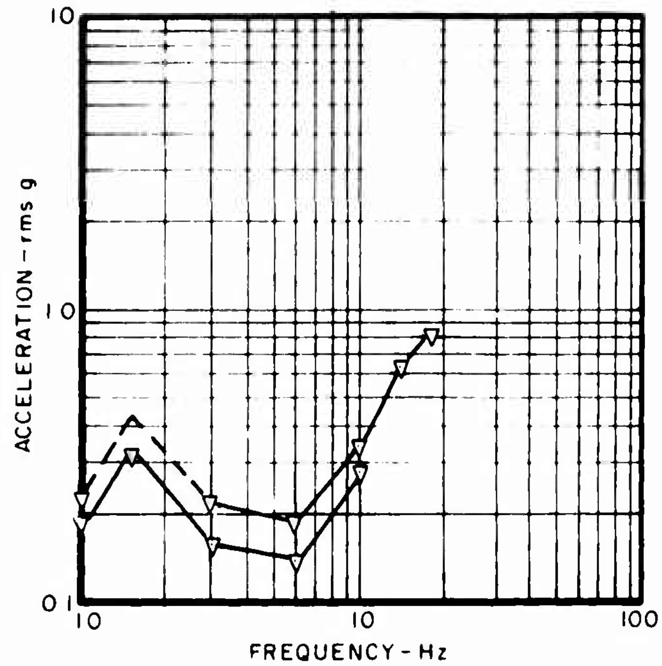


Figure 19. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Total Error (Ref 35)

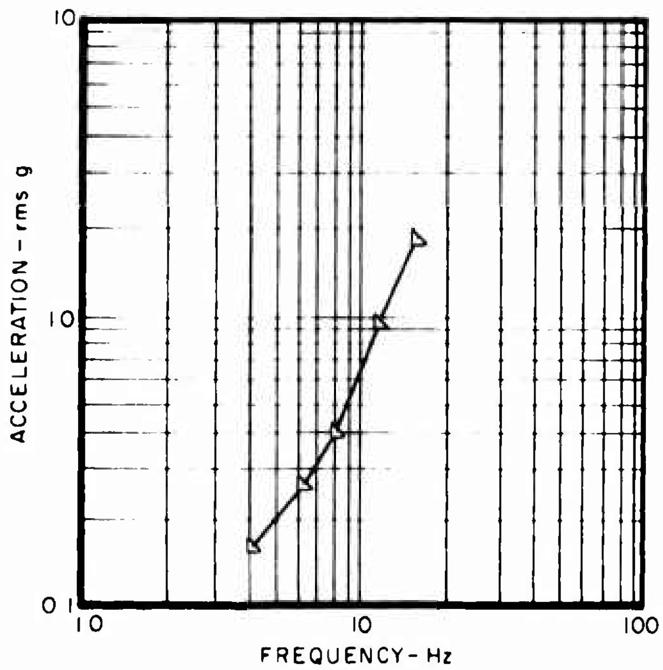


Figure 20. Acceleration as a Function of Vertical Vibration Frequency for Constant Relative Total Error (Ref 29)

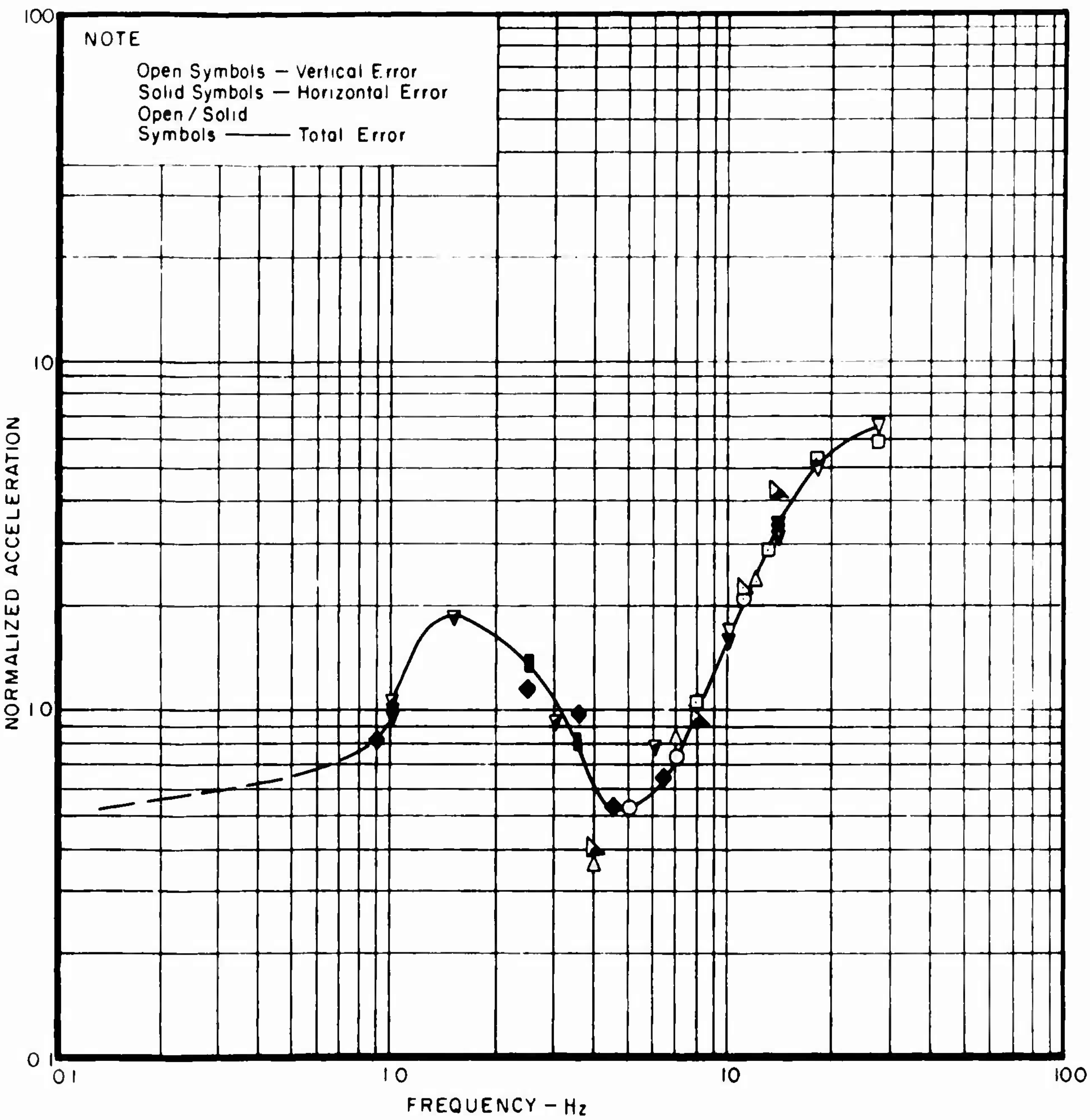


Figure 21. Normalized Constant Relative Tracking Error Curve for Vertical Vibration

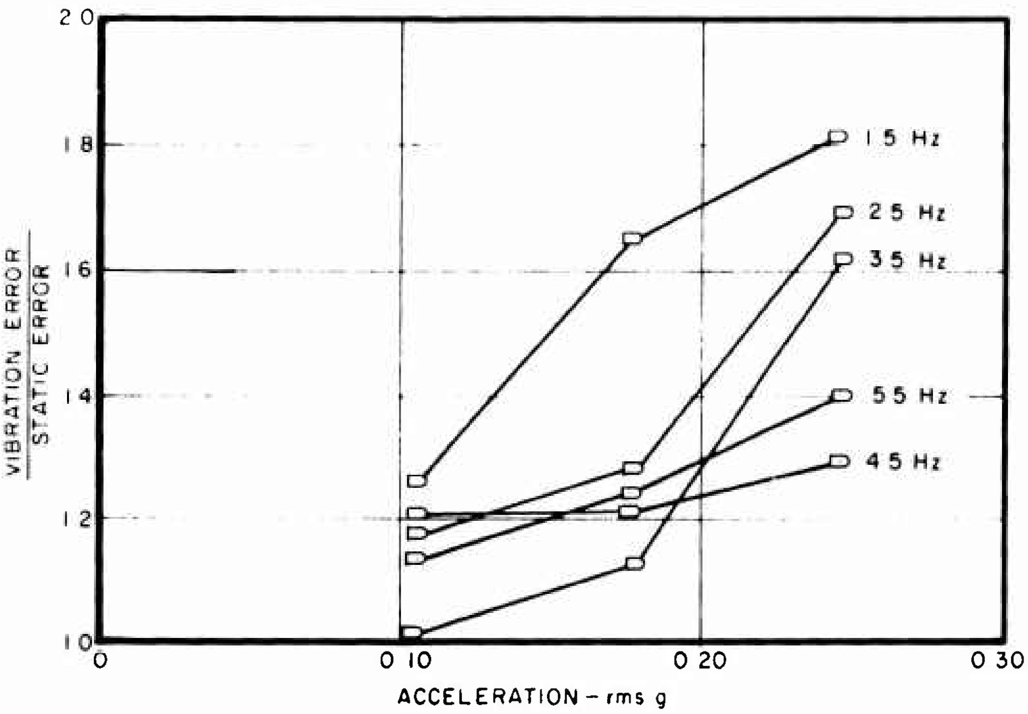


Figure 22. Relative Horizontal Tracking Error as a Function of Lateral Vibration Intensity and Frequency (Ref 27)

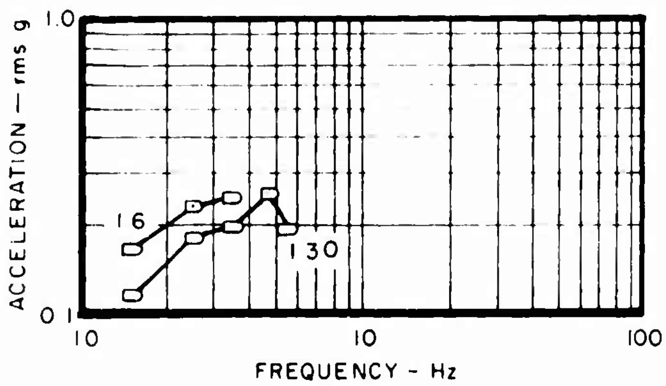


Figure 23. Acceleration as a Function of Lateral Vibration Frequency for Constant Relative Horizontal Error (Ref 27)

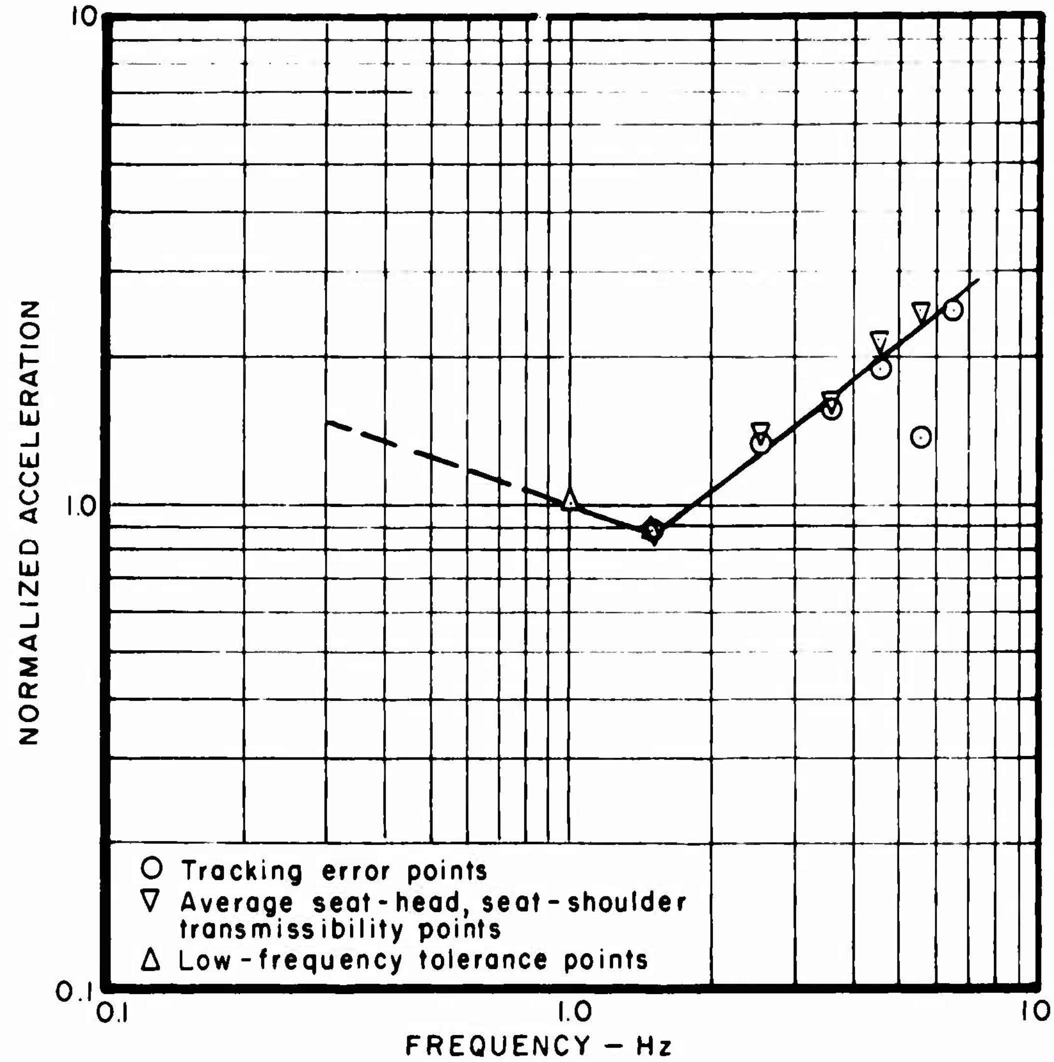


Figure 24. Normalized Constant Relative Tracking Error Curve for Lateral Vibration

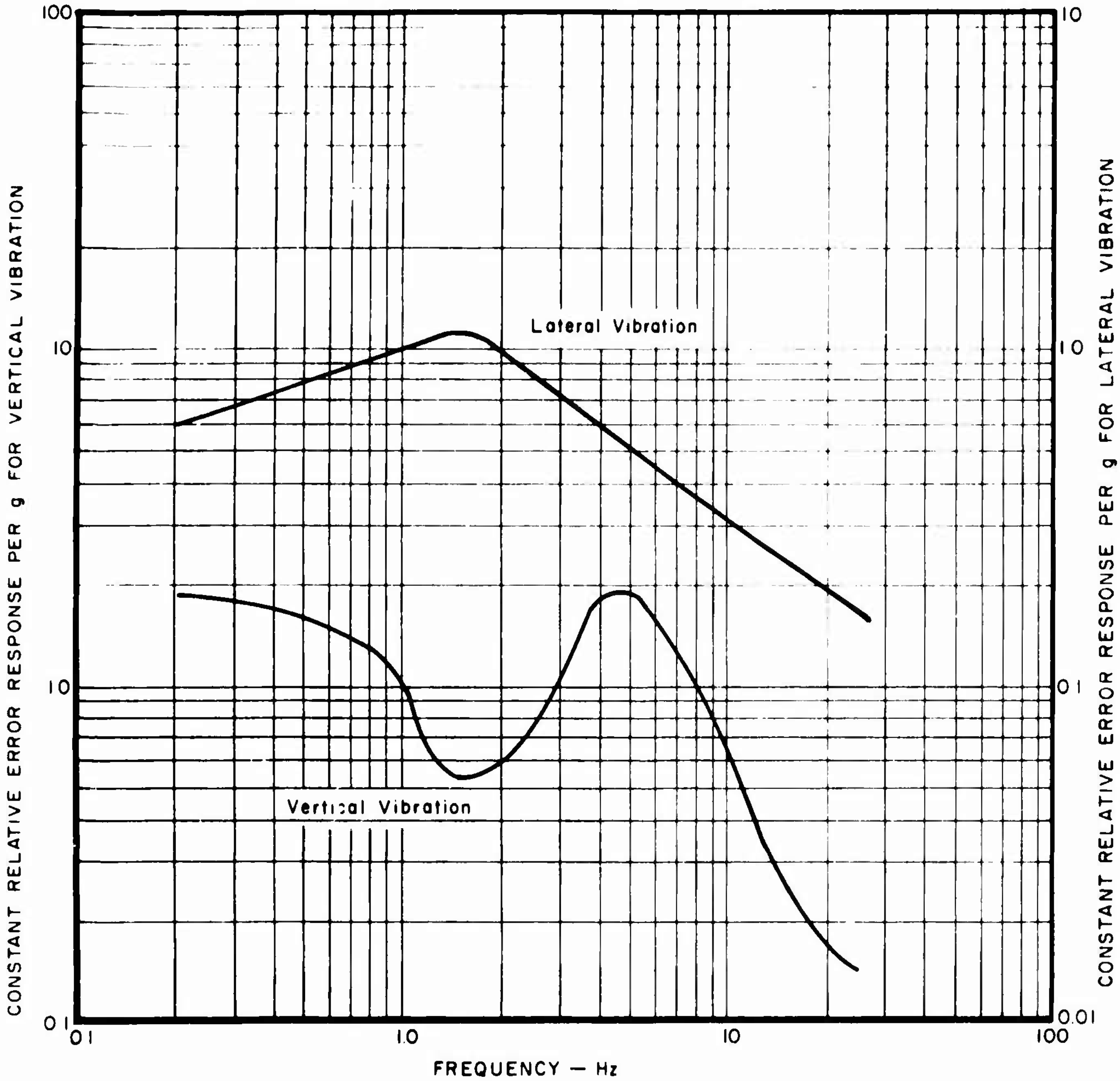


Figure 25. Normalized Human Tracking Error Frequency Response Functions for Vertical and Lateral Vibration

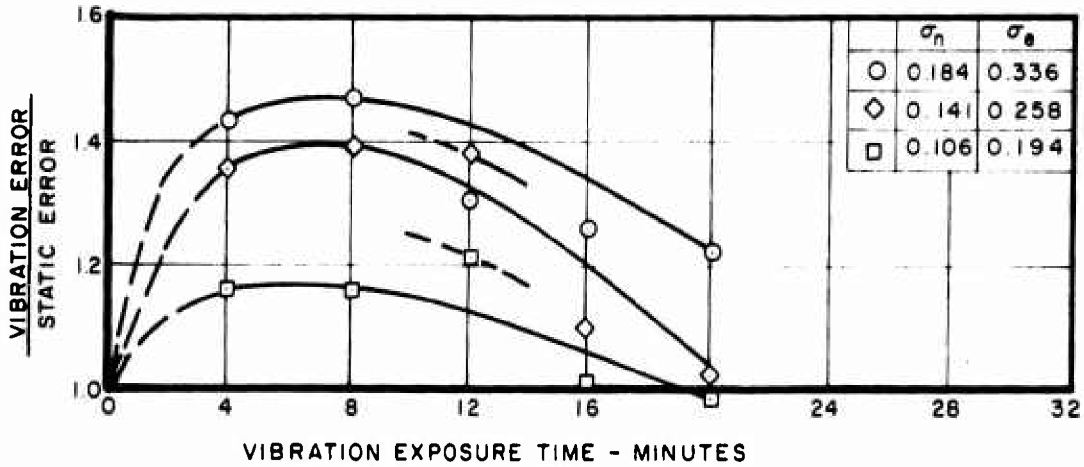


Figure 26a. Relative Vertical Tracking Error Versus Exposure Time (Ref 3)

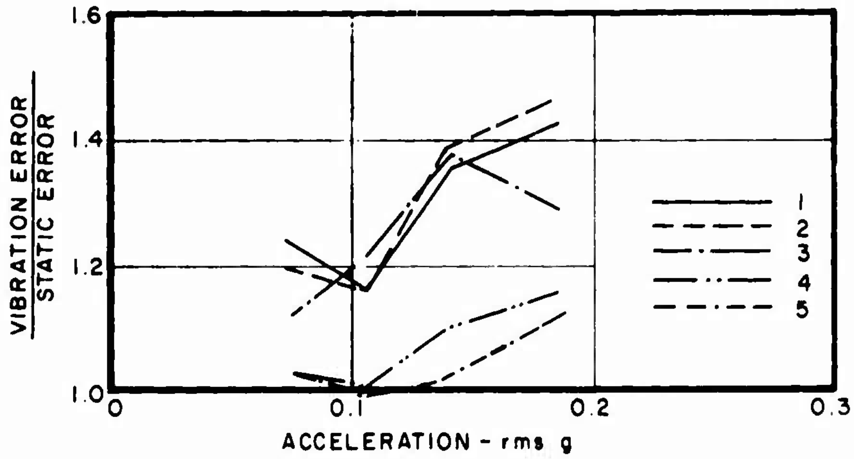
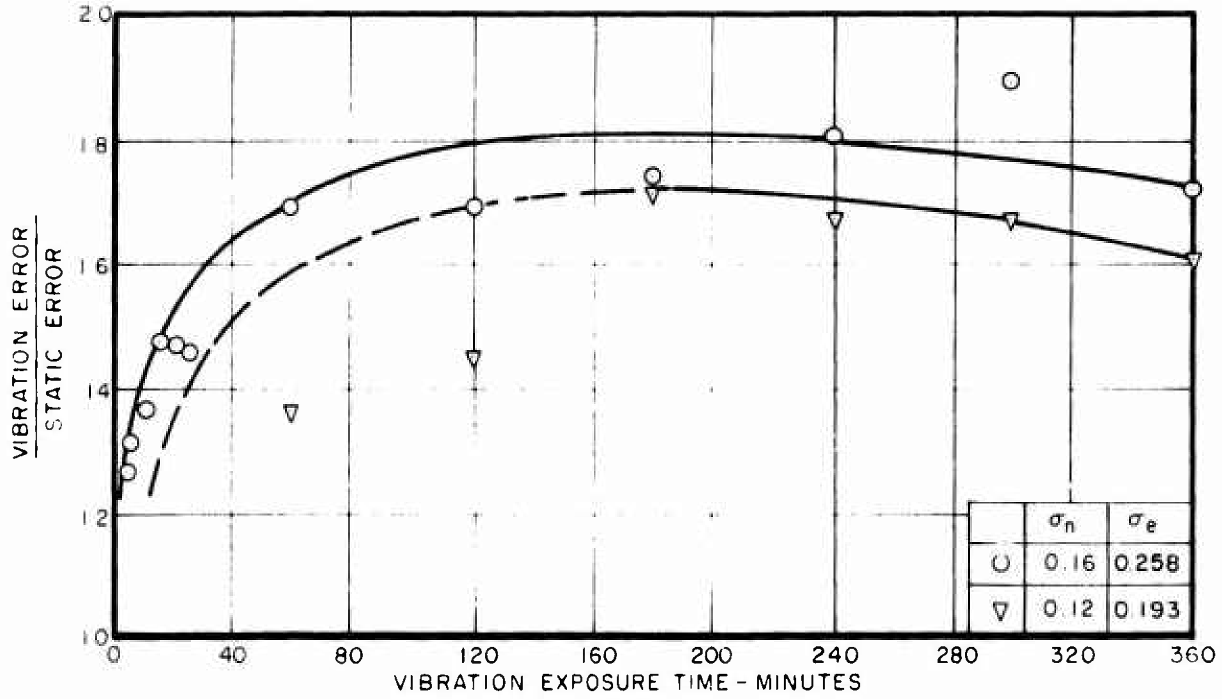


Figure 26b. Relative Vertical Tracking Error as a Function of Acceleration and Trial (Ref 3)



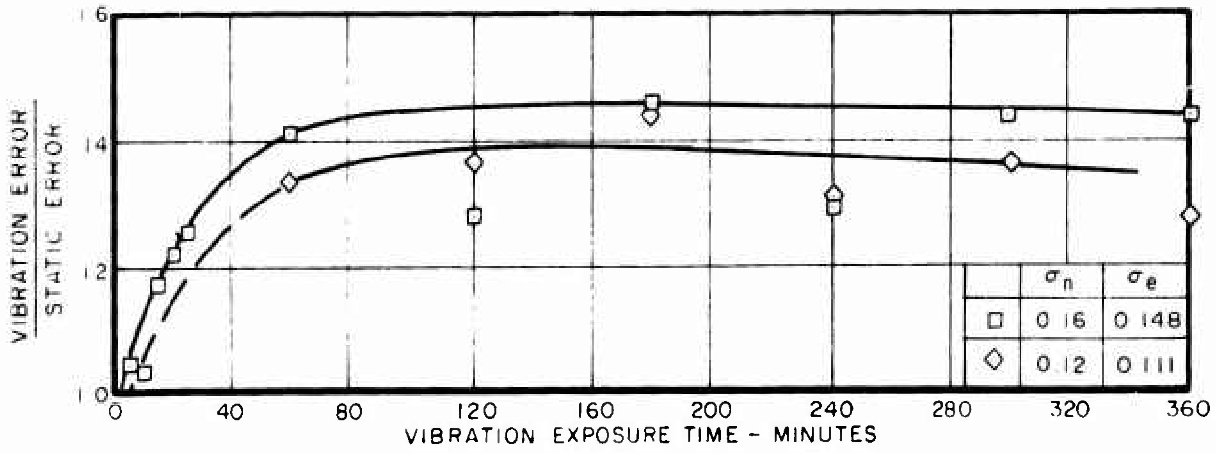


Figure 27a and b. Relative Vertical Tracking Error Versus Exposure Time (Ref 7)

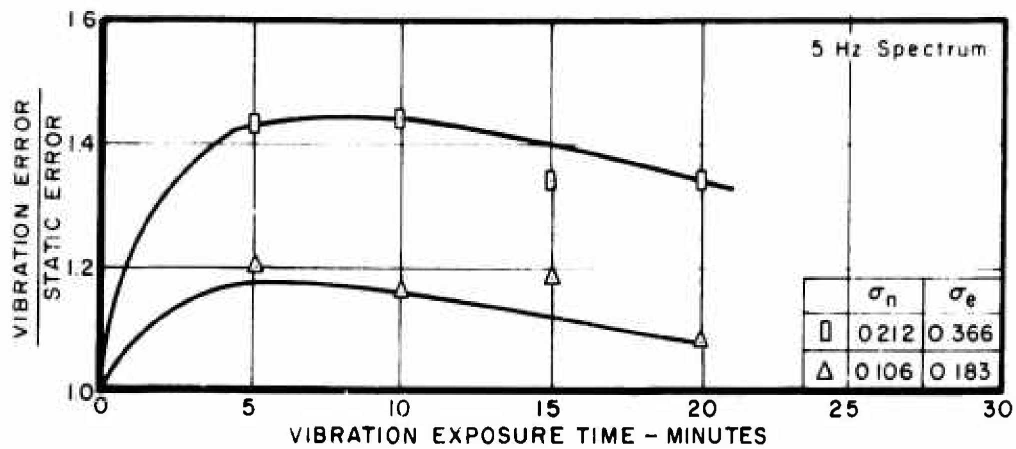


Figure 28a. Relative Vertical Tracking Error Versus Exposure Time (Ref 5)

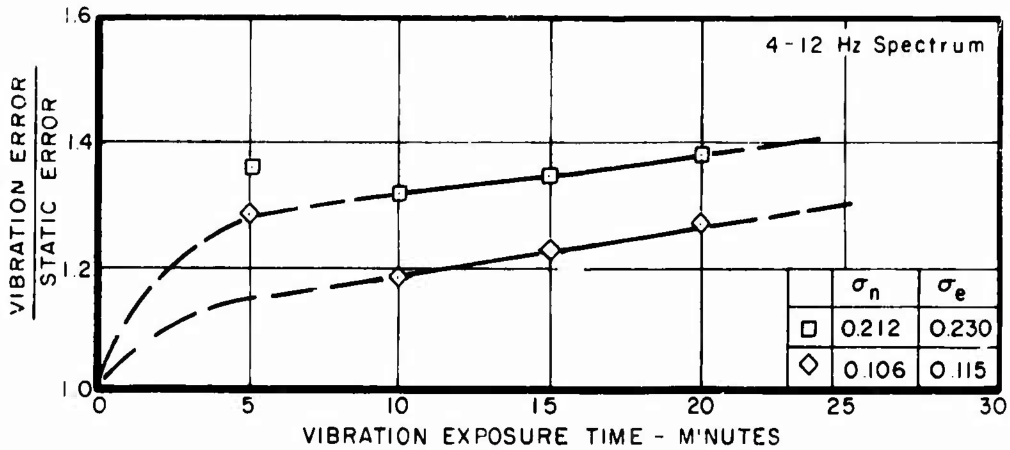


Figure 28c. Relative Vertical Tracking Error Versus Exposure Time (Ref 5)

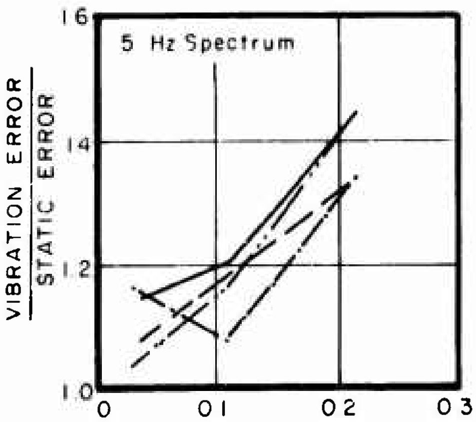


Figure 28b. Relative Tracking Error as a Function of Acceleration and Trial

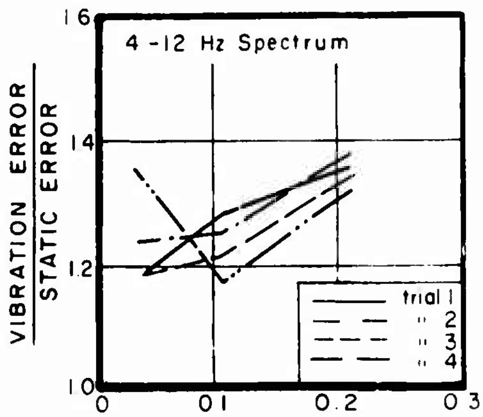


Figure 28d. Relative Tracking Error as a Function of Acceleration and Trial

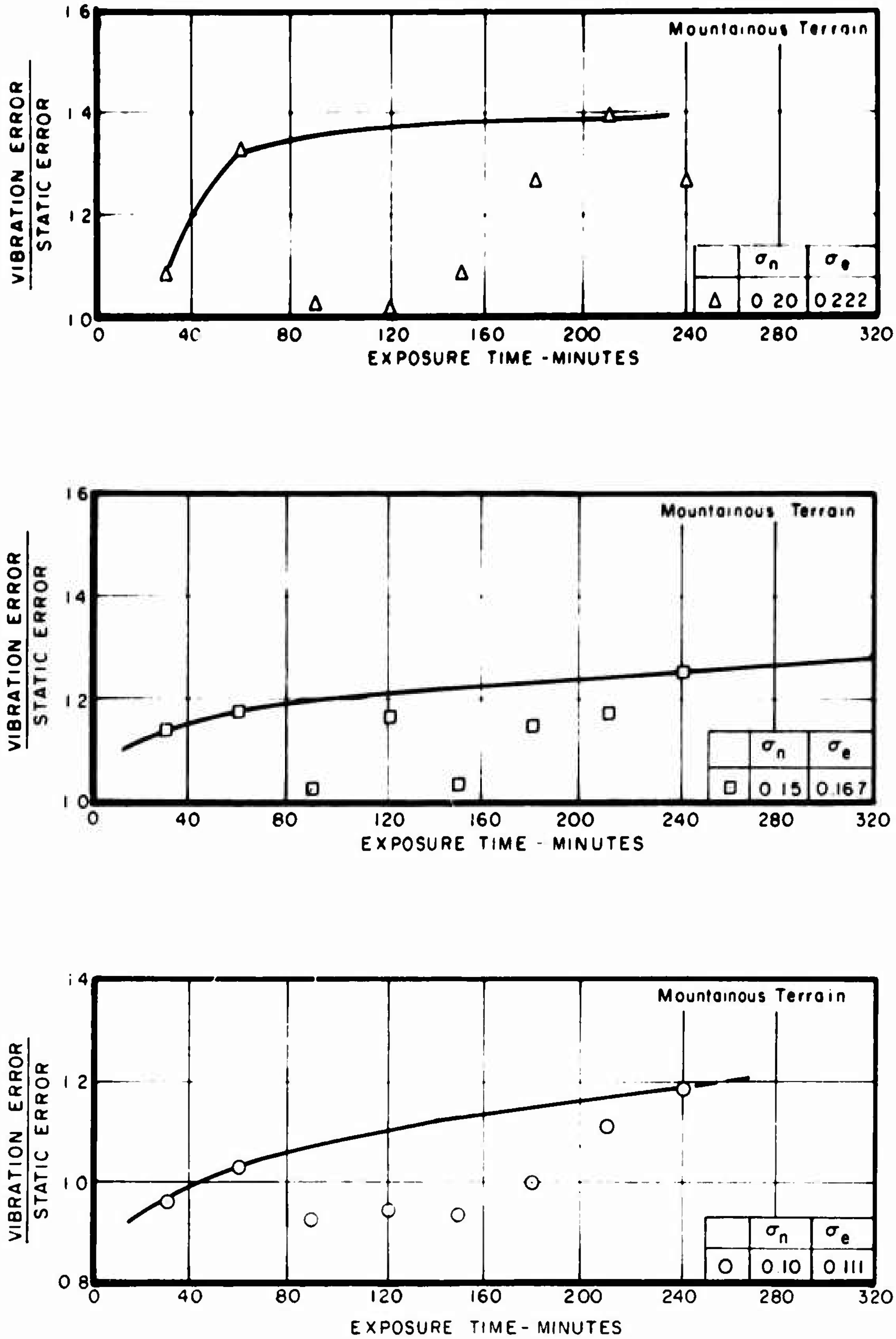


Figure 29a, b, c. Relative Tracking Error Versus Exposure Time (Ref 22)

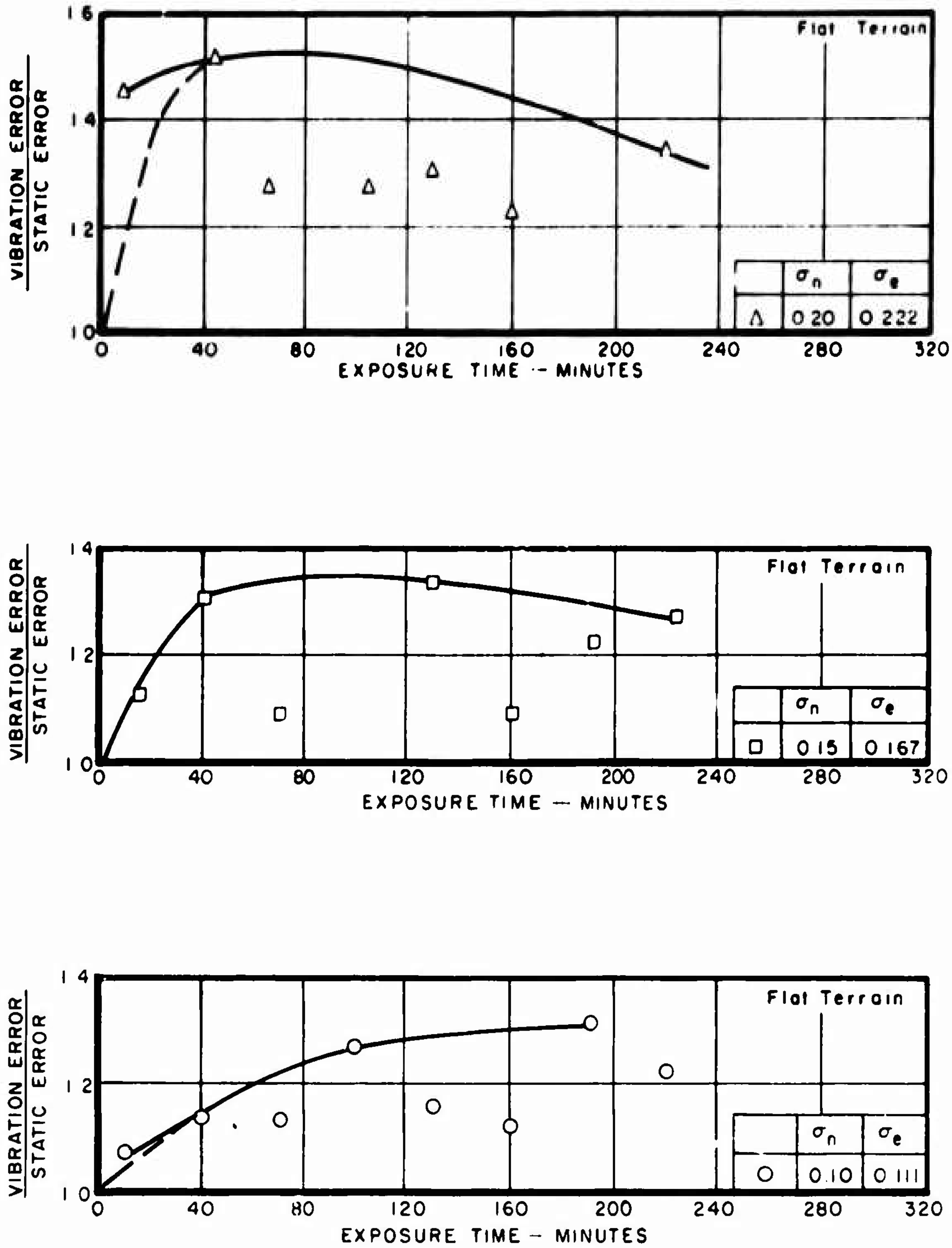


Figure 30a, b, c. Relative Tracking Error Versus Exposure Time (Ref 22)

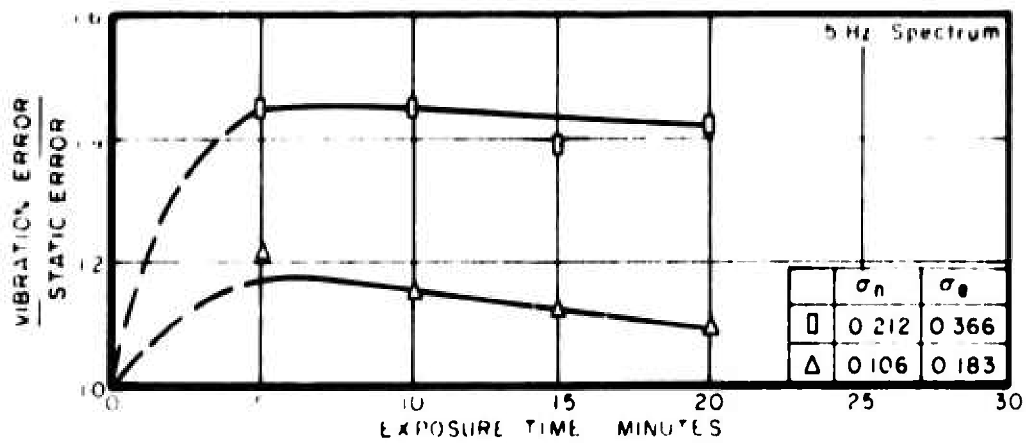


Figure 31a. Relative Horizontal Tracking Error Versus Exposure Time (Ref 5)

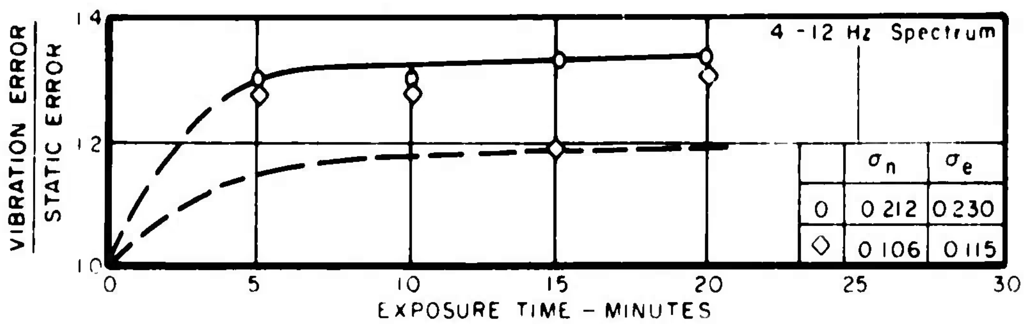


Figure 31c. Relative Horizontal Tracking Error Versus Exposure Time (Ref 5)

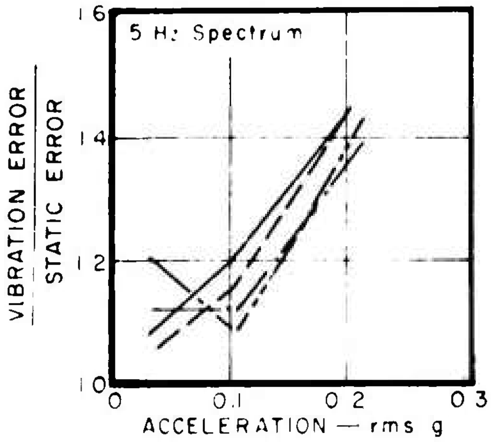


Figure 31b. Relative Horizontal Tracking Error as a Function of Acceleration and Trial (Ref 5)

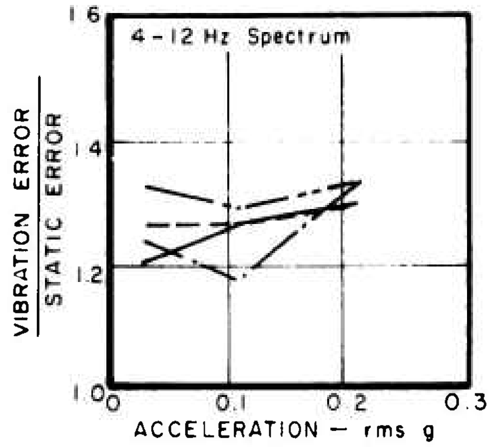
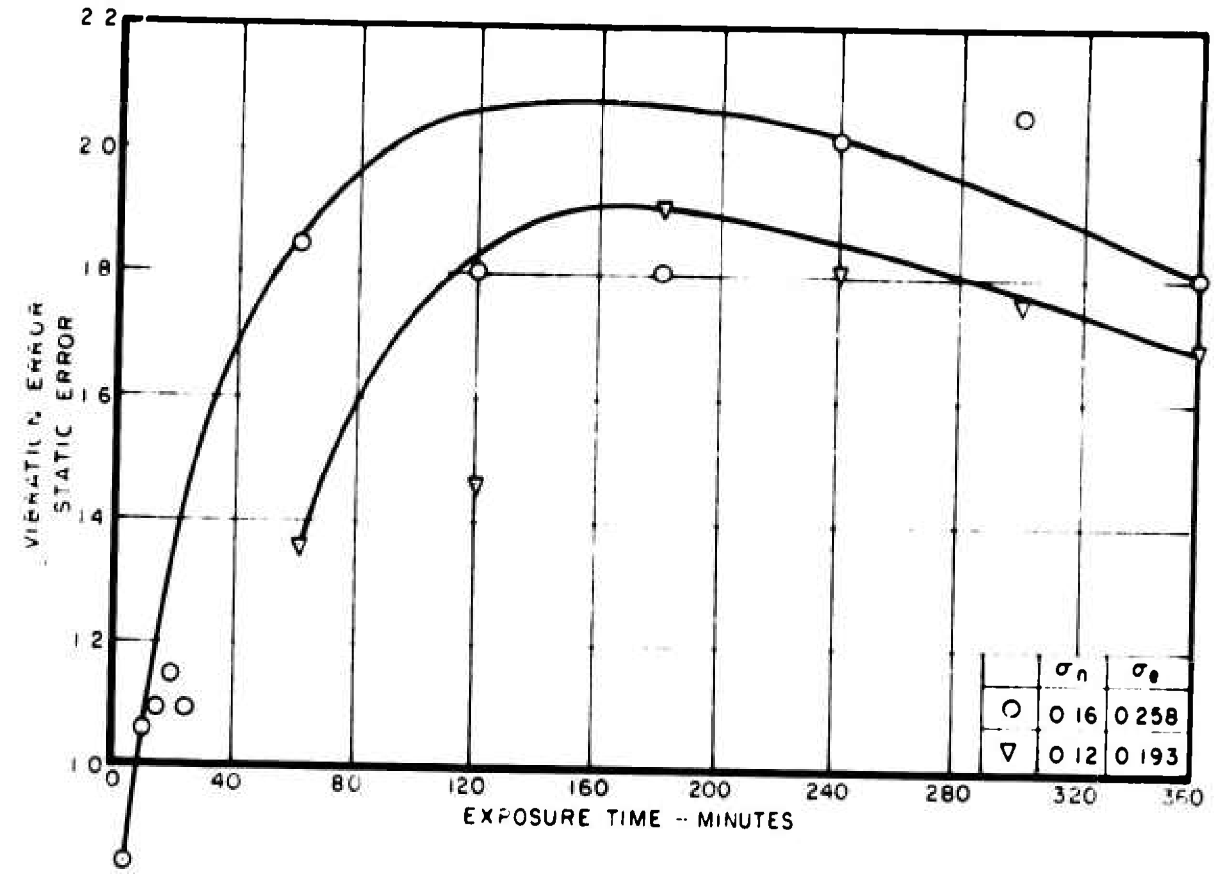


Figure 31d. Relative Horizontal Tracking Error as a Function of Acceleration and Trial (Ref 5)



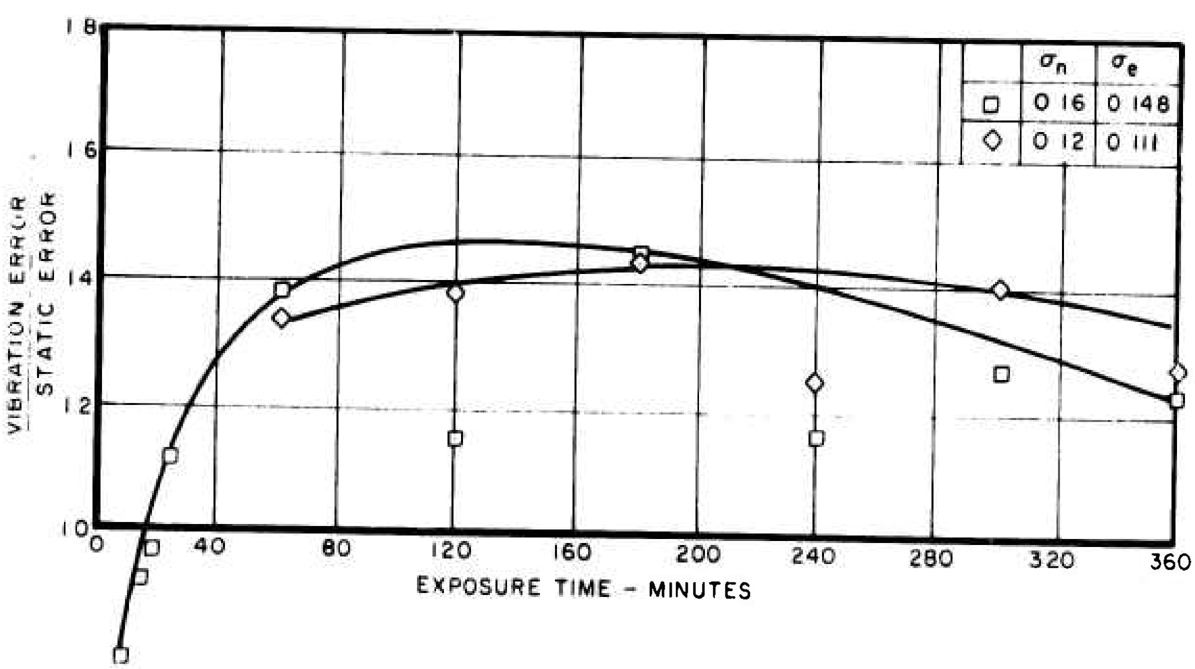


Figure 32a and b. Relative Horizontal Tracking Error Versus Exposure Time (Ref 7)

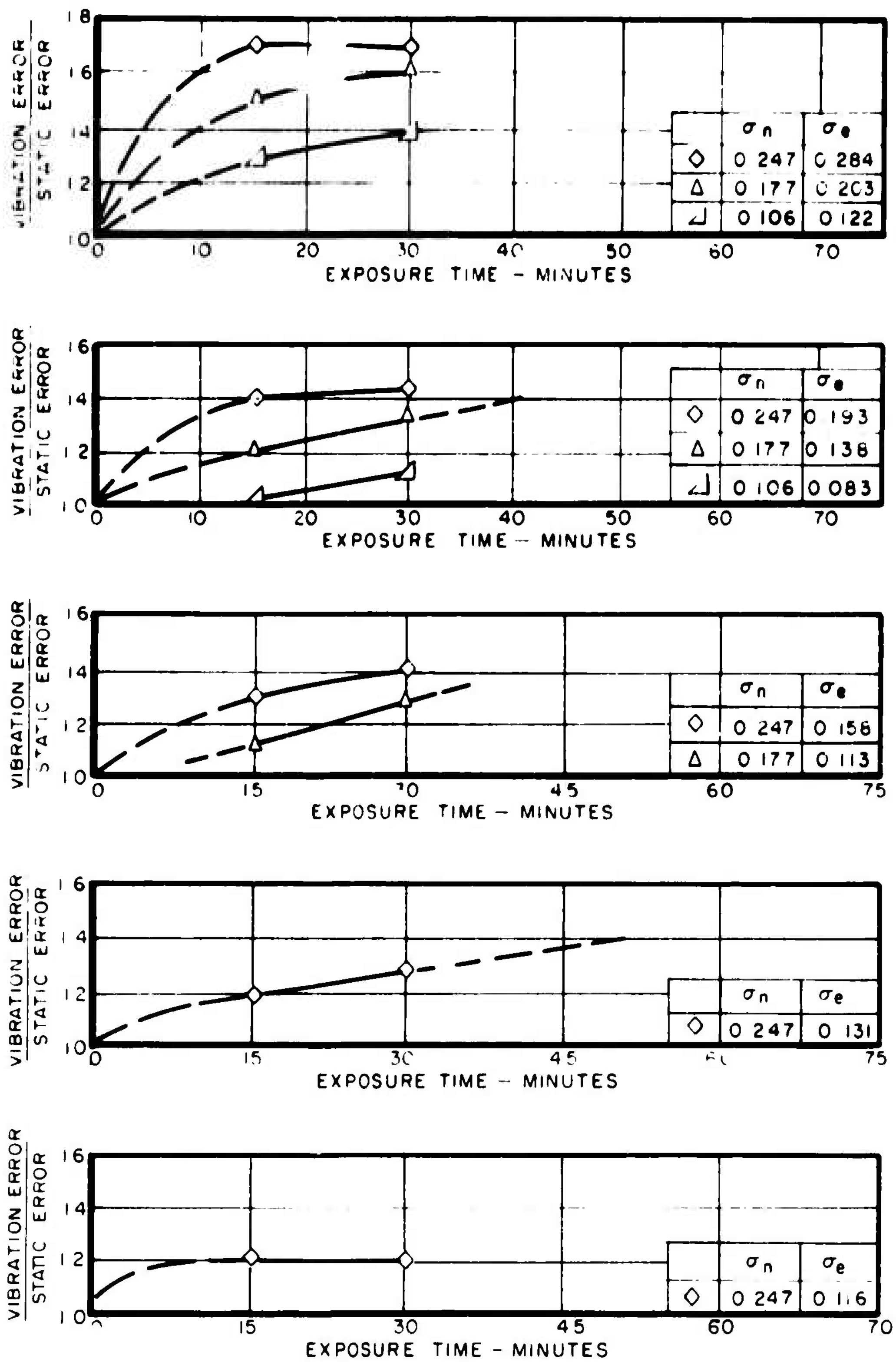


Figure 33a, b, c, d, e. Relative Horizontal Tracking Error Versus Exposure Time for Lateral Vibration (Ref 27)

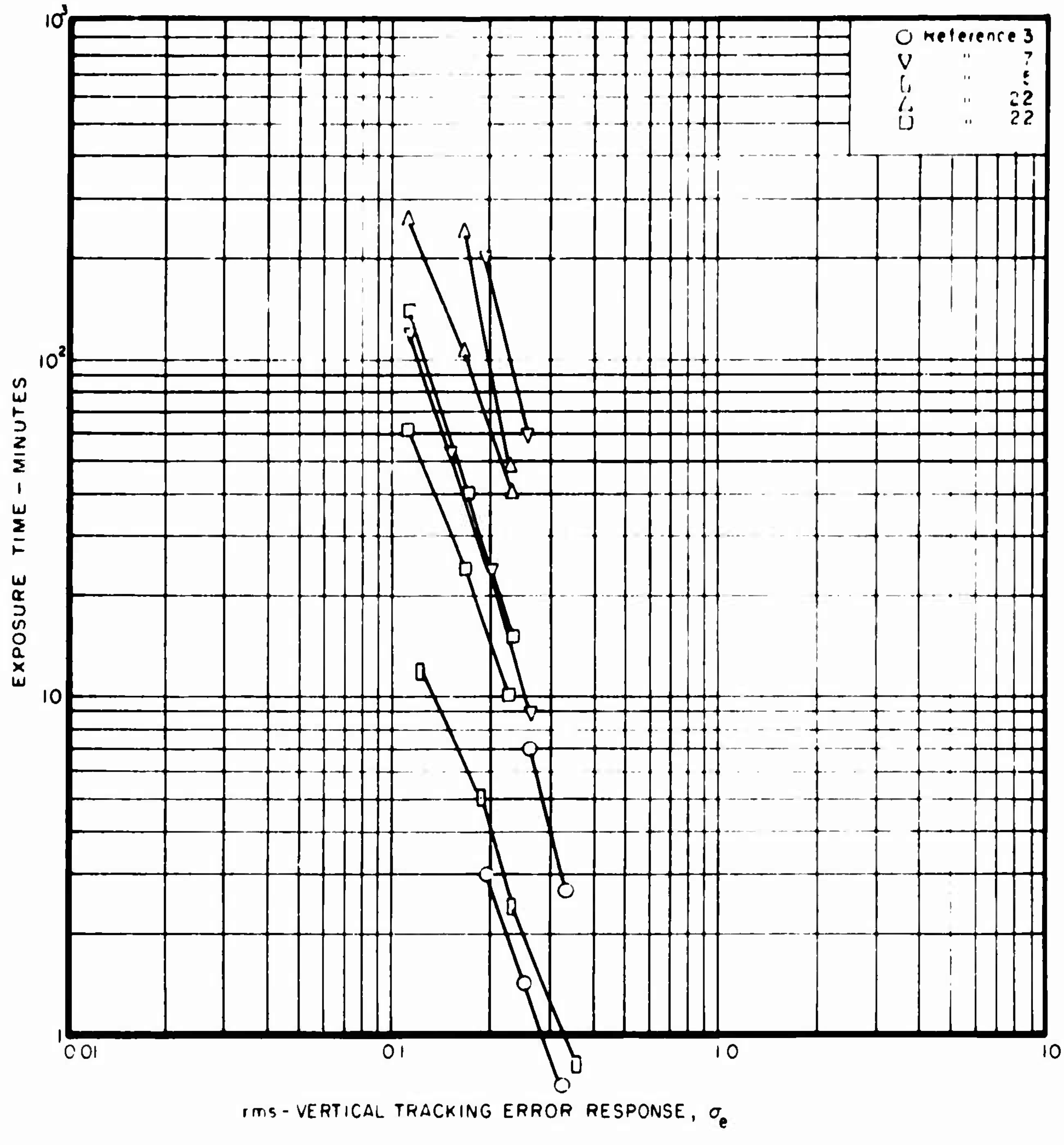


Figure 34. Constant Vertical Tracking Effectiveness for Vertical Vibration

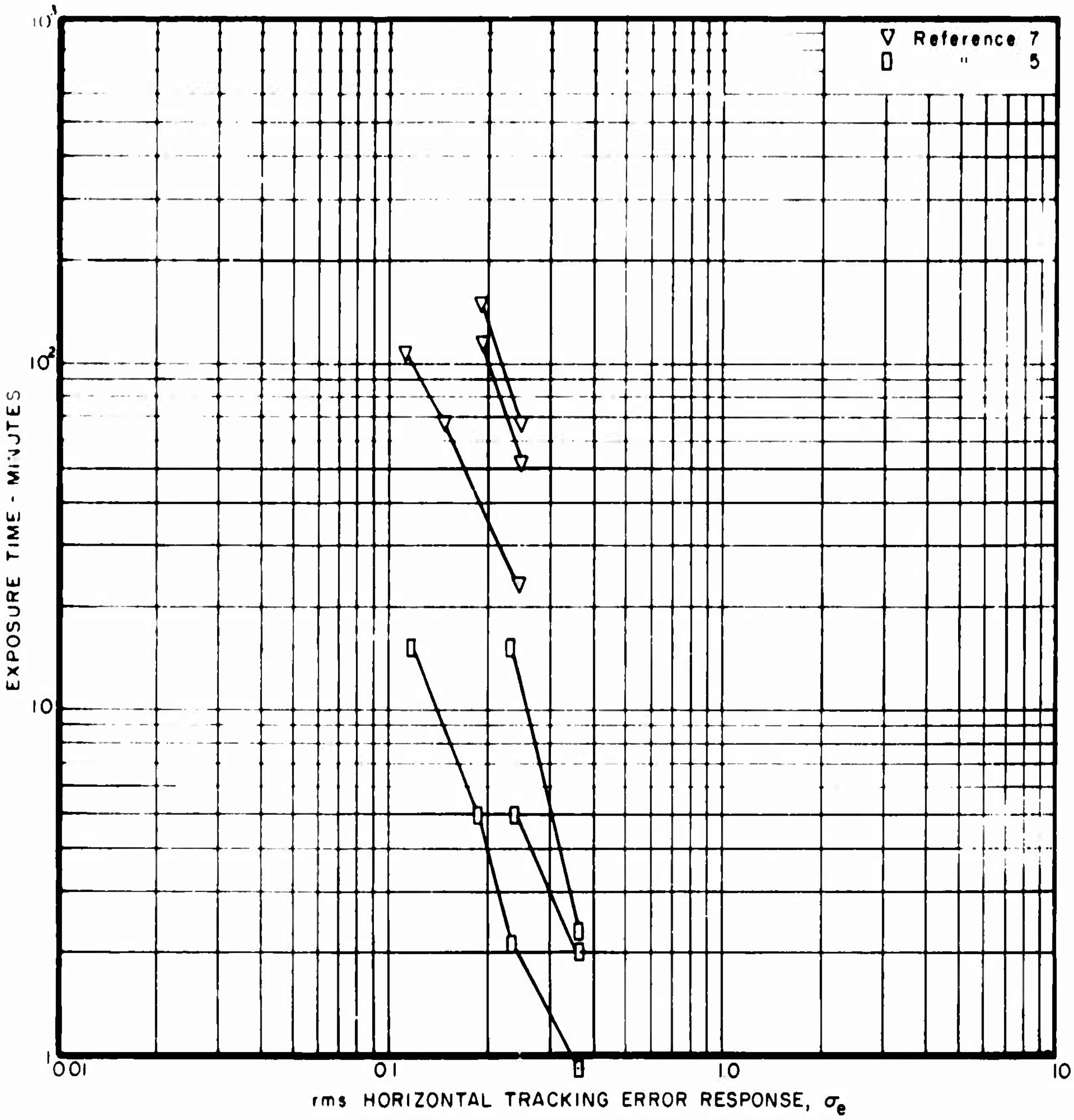


Figure 35. Constant Horizontal Tracking Effectiveness for Vertical Vibration

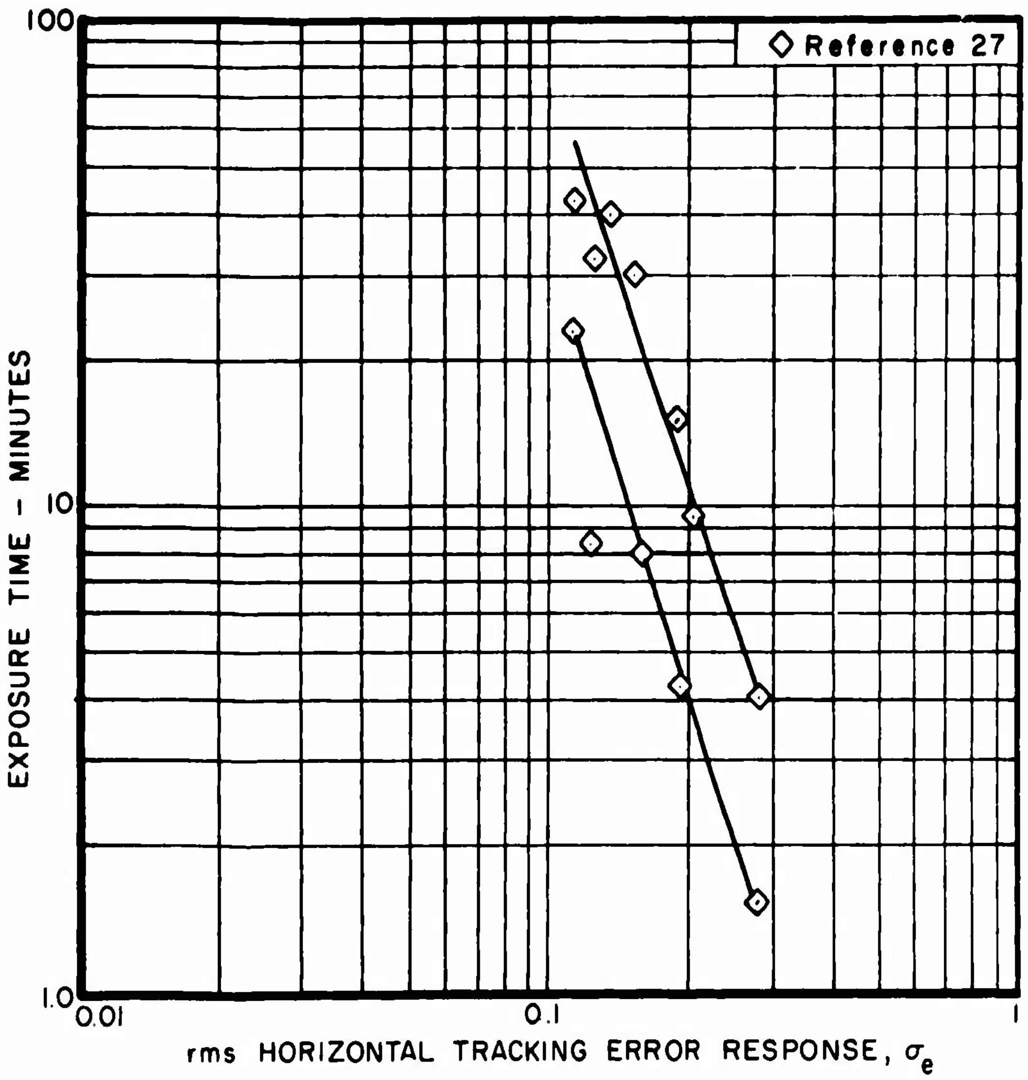


Figure 36. Constant Horizontal Tracking Effectiveness for Lateral Vibration

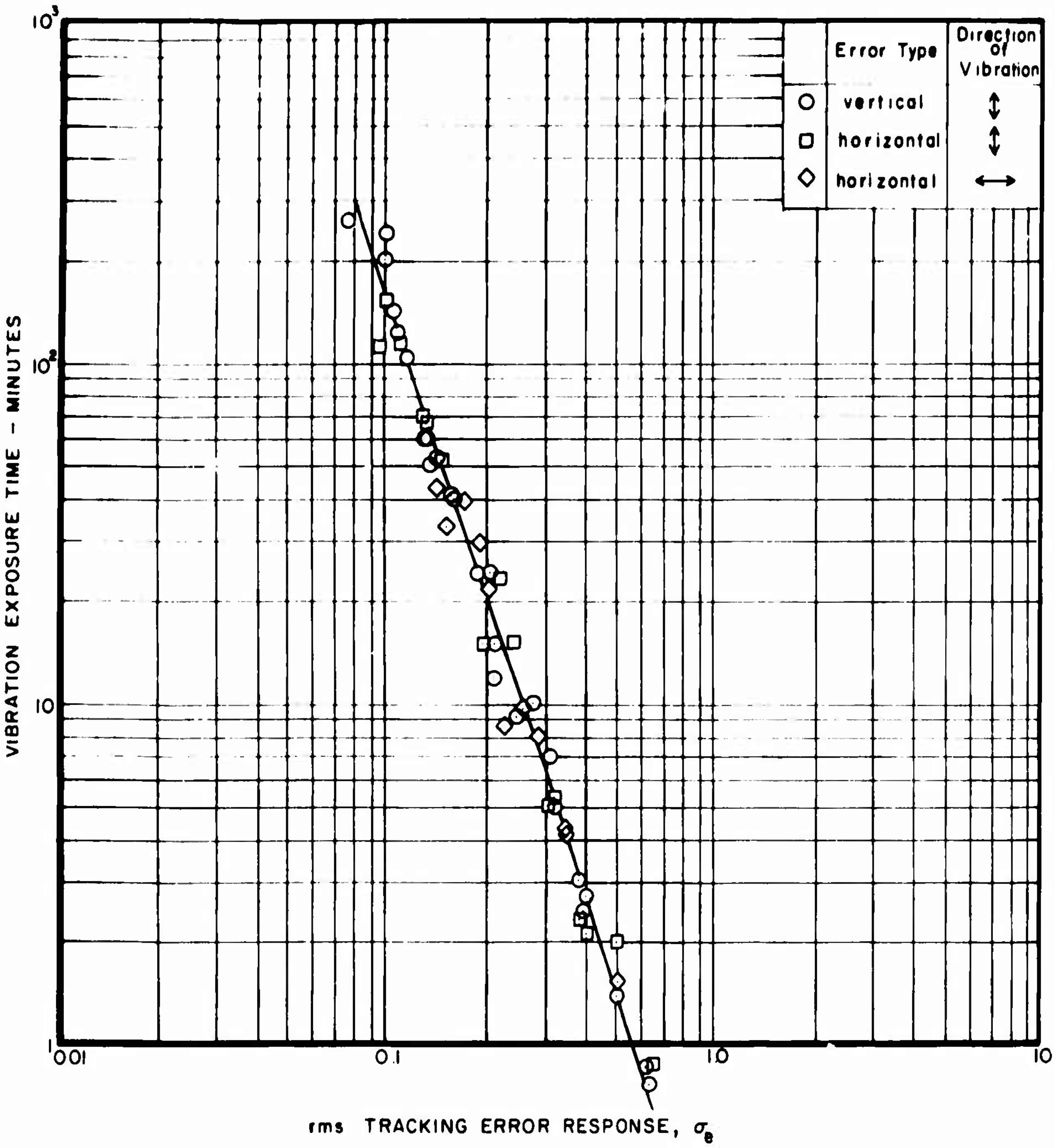


Figure 37. Normalized Constant Tracking Effectiveness in a Vibration Environment

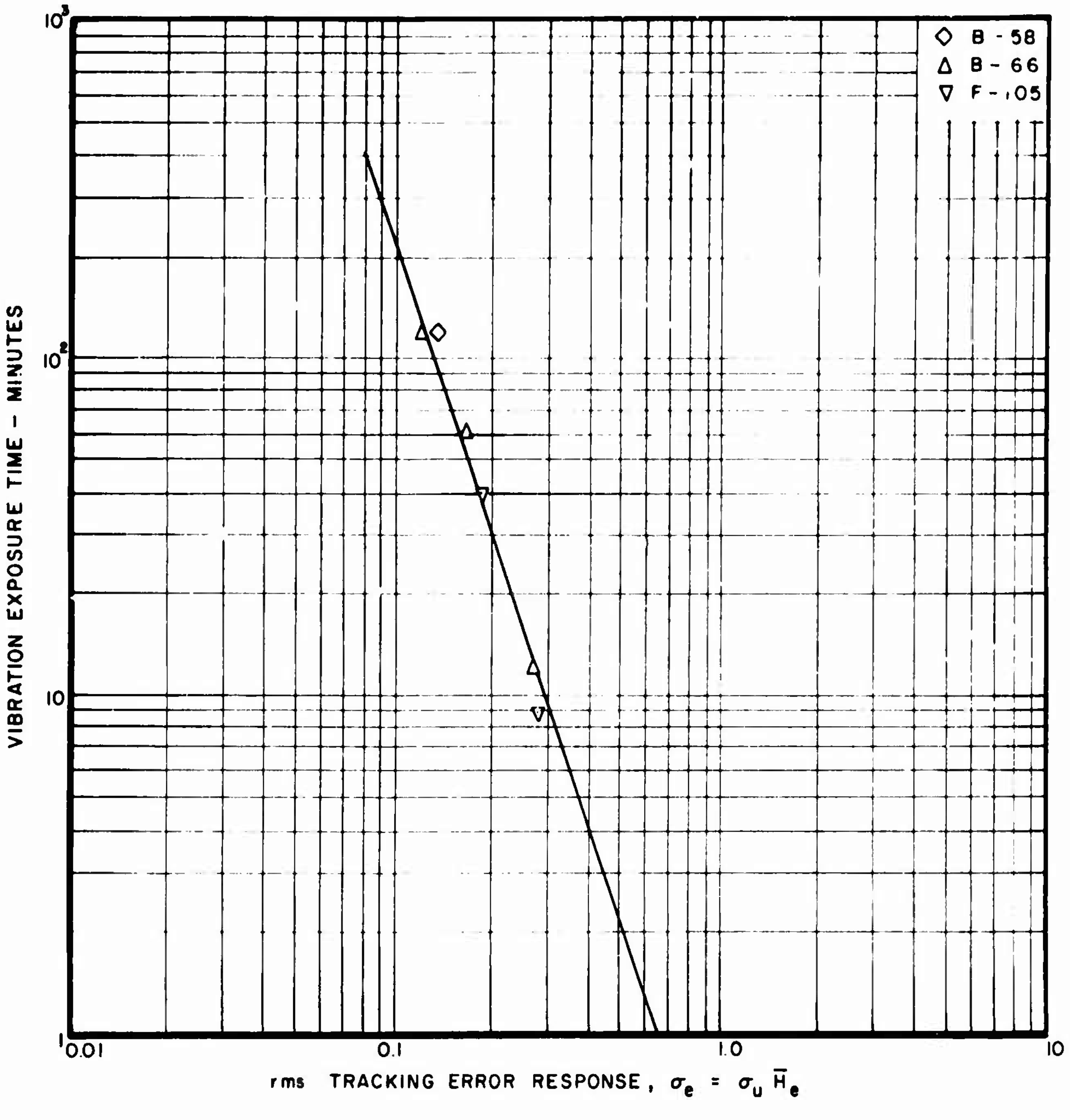


Figure 38. Pilot Exposure Time Estimates as a Function of RMS Crew Task Error Response for Vertical Vibration

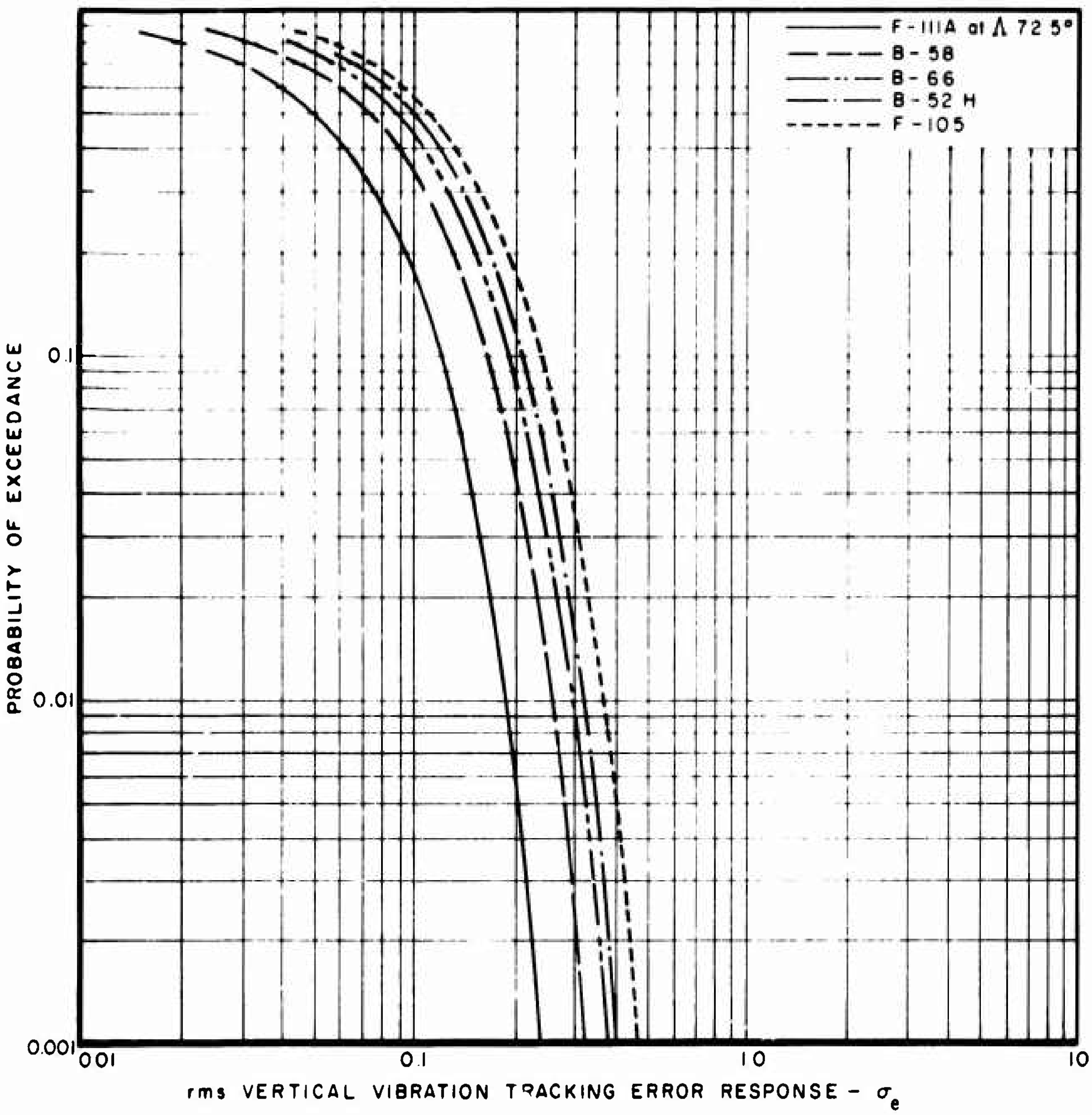


Figure 39. Probability of Exceedance of RMS Crew Task Error Response for Various Aircraft

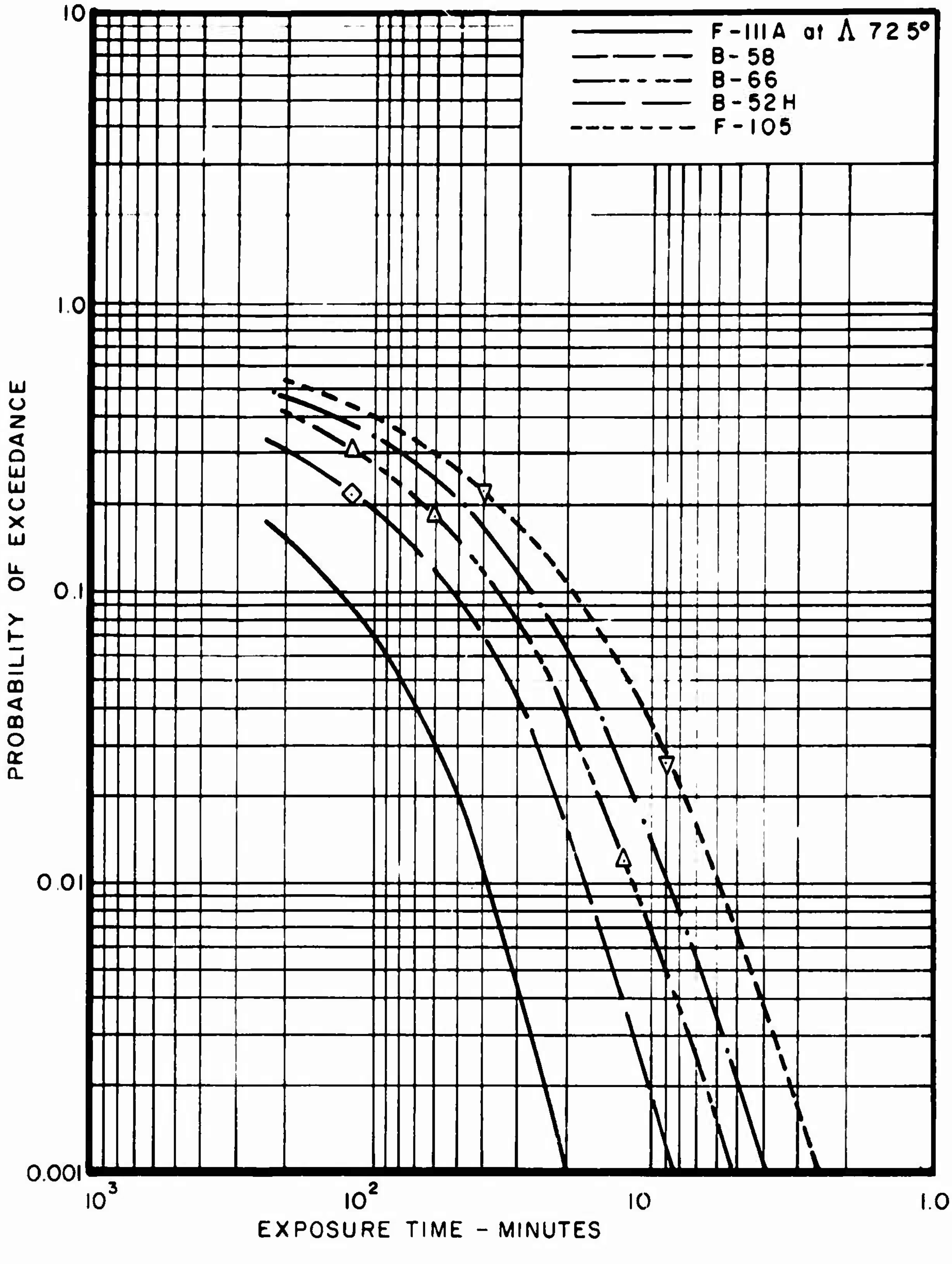


Figure 40. Probability of Exceeding Pilot Effectiveness Levels

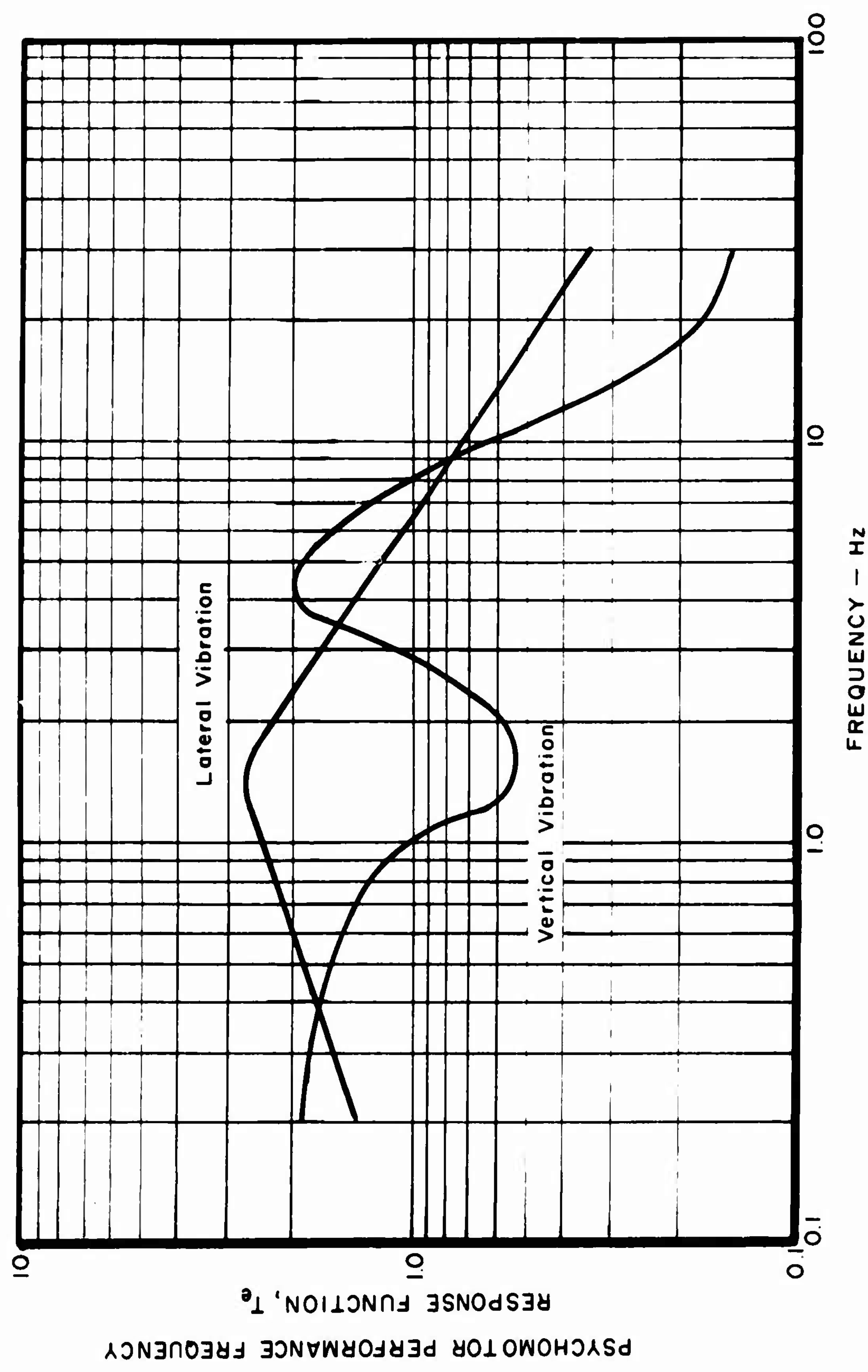


Figure 41. Universal Psychomotor Task Frequency Response Functions for Vertical and Lateral Vibration

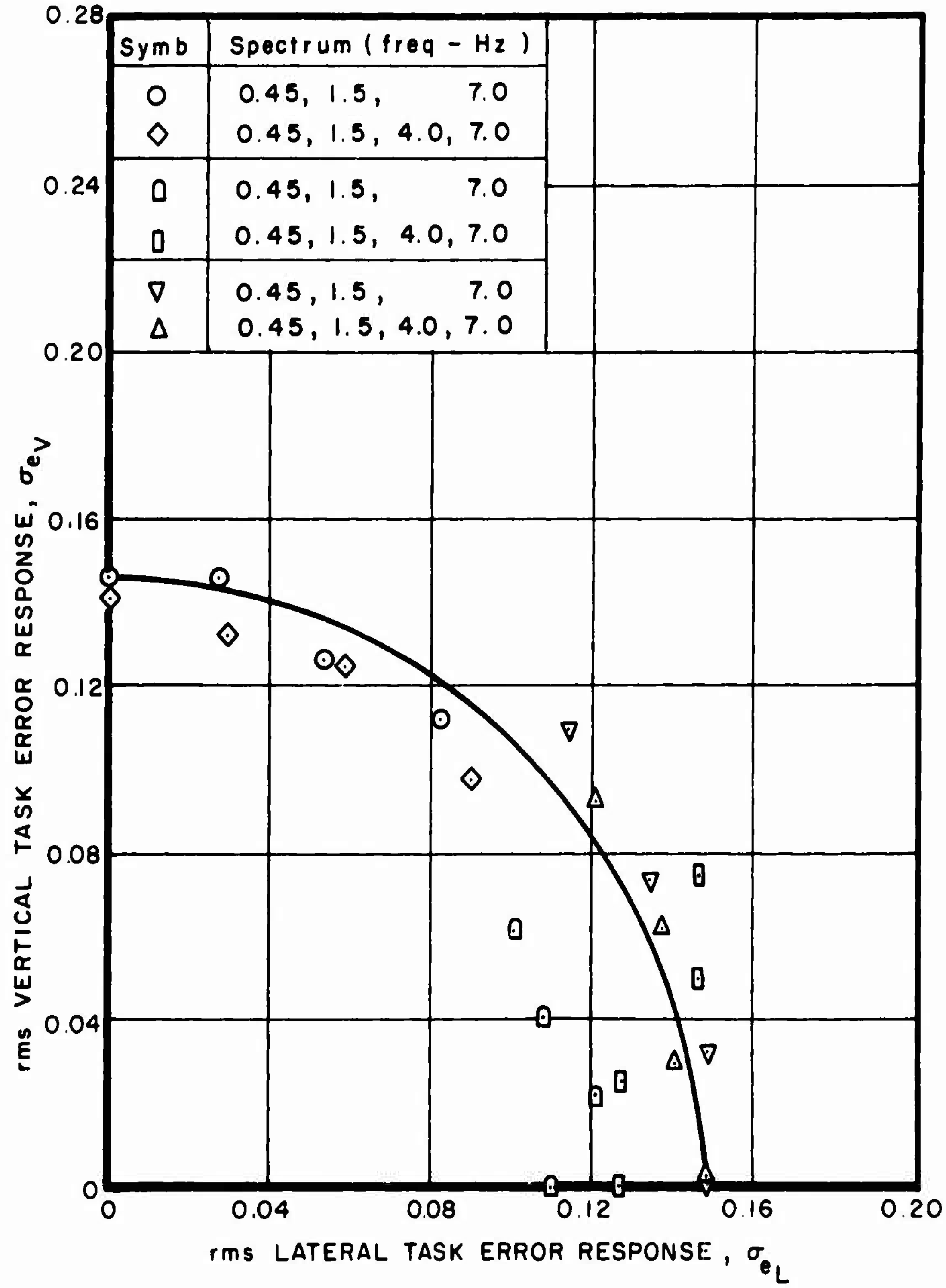


Figure 42. Predicted Variation of Vertical and Lateral RMS Task Error Response Based on Reference 53 RMS g Discomfort Results

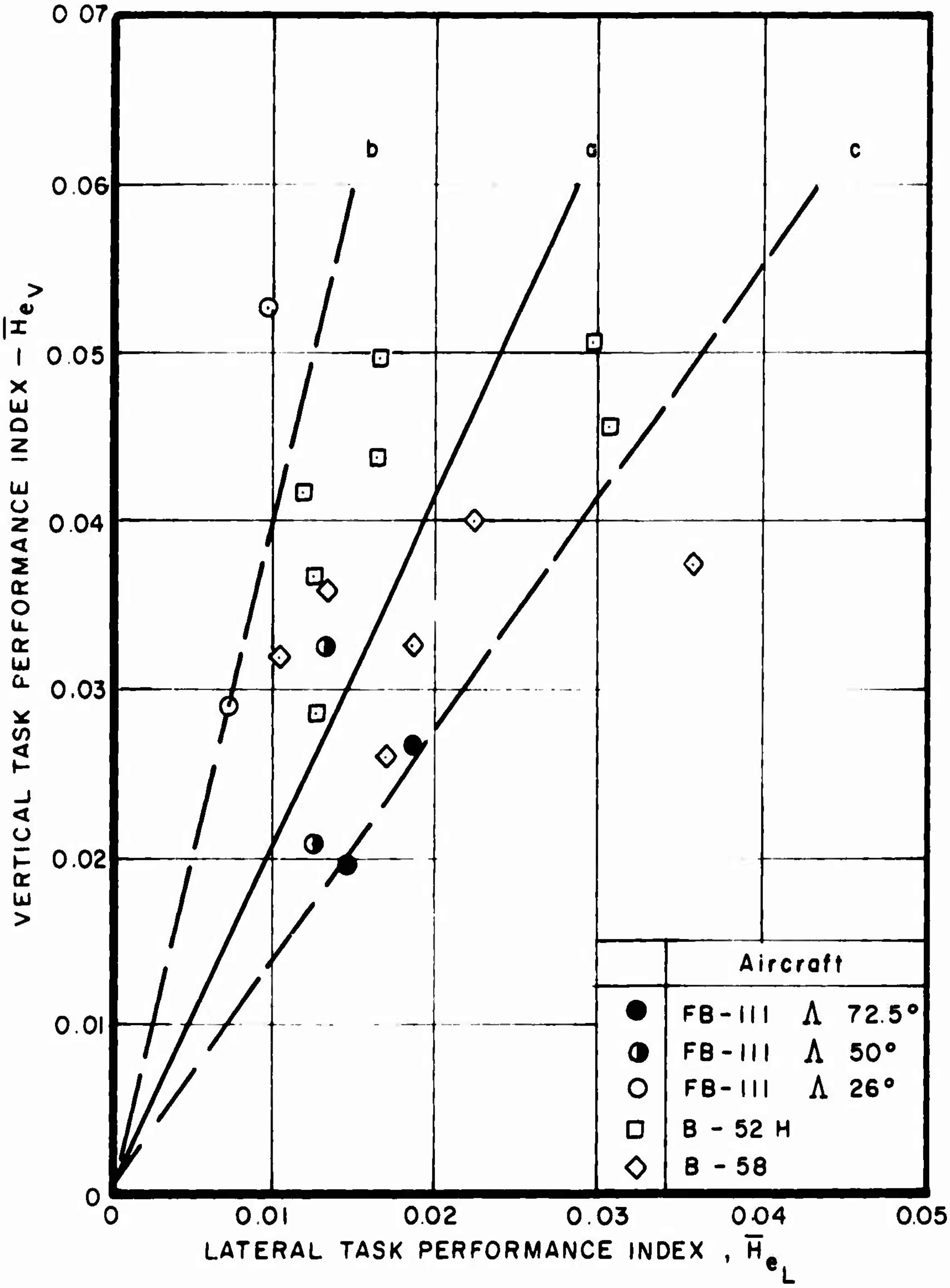


Figure 43. Variability of Vertical and Lateral Task Performance Indexes for Three Aircraft

APPENDIX I

TURBULENCE DESCRIPTION

TABLE VII

TURBULENCE FIELD PARAMETERS

MISSION SEGMENT	ALTITUDE	DIRECTION	P_1	b_1	P_2	b_2	L(ft)
Low-Level Contour	0- 1000 ft	Vertical	1.0	2.7	10^{-5}	10.65	500
Low-Level Contour	0- 1000 ft	Lateral	1.0	3.1	10^{-5}	14.06	500
Climb, Cruise, Descent	0- 1000 ft	Vert. & Lat.	1.0	2.51	0.005	5.04	500
Climb, Cruise, Descent	1,000- 2,500 ft	Vert. & Lat.	0.42	3.02	0.0033	5.94	1750
Climb, Cruise, Descent	2,500- 5,000 ft	Vert. & Lat.	0.30	3.42	0.0020	8.17	2500
Climb, Cruise, Descent	5,000-10,000 ft	Vert. & Lat.	0.15	3.59	0.00095	9.22	2500
Climb, Cruise, Descent	10,000-20,000 ft	Vert. & Lat.	0.062	3.27	0.00028	10.52	2500
Climb, Cruise, Descent	20,000-30,000 ft	Vert. & Lat.	0.025	3.15	0.00011	11.88	2500
Climb, Cruise, Descent	30,000-40,000 ft	Vert. & Lat.	0.011	2.93	0.000095	9.84	2500
Climb, Cruise, Descent	40,000-50,000 ft	Vert. & Lat.	0.0046	3.28	0.000115	8.81	2500
Climb, Cruise, Descent	50,000-60,000 ft	Vert. & Lat.	0.002	3.82	0.000078	7.04	2500
Climb, Cruise, Descent	60,000-70,000 ft	Vert. & Lat.	0.00088	2.93	0.000057	4.33	2500

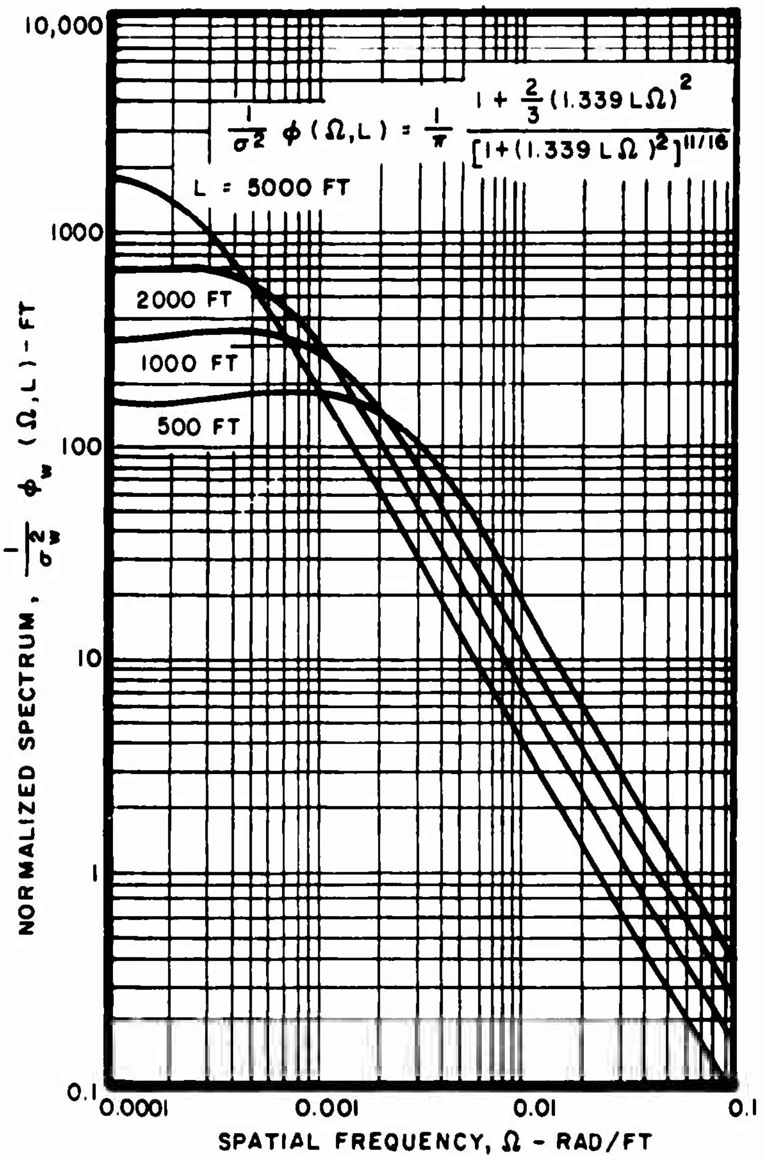


Figure 44. Von Karman Spectral Form for Turbulence Velocity

APPENDIX II

COMPARISON OF SUBJECTIVE OBJECTIONABLE RESPONSE AND DERIVED CONSTANT TRACKING ERROR RESPONSE CURVES

In a survey of the literature concerning subjective evaluation of comfort during vibration, a considerable variety of conclusions regarding the shape of the tolerance curve is evident. When, in addition to subjective discomfort, the effects of vibration on subject performance are considered, hardly any agreement in the shape of the tolerance curves for discomfort and performance would be expected. Figures 21 and 24 present the normalized tracking error tolerance curves for vertical and lateral vibration as developed in this report. Figure 45 through 48 present the objectionable tolerance curves for passenger discomfort as derived from References 53 and 61. These curves were determined from simulator tests using representative airliner passenger seats. Any comparison of vibration tolerance curves, whether based on discomfort or performance, must of necessity consider differences between hard or soft seats used.

The observation has been made that the use of seat cushions can substantially change the permissible g values to a subject. Only the actual vibrations transmitted to the subject should therefore be related. Any soft seat tolerance evaluation results must be modified by the soft seat attentuation characteristics before comparisons with hard seat results are made. Figure 49 presents the transmissibility characteristics of a conventional foam cushion. These transmissibility characteristics were applied to the 80-percentile tolerance curves of Figures 47 and 48. It was decided to use the 80-percentile data for a number of reasons. The actual shape of the tolerance curve is very much dependent on the purpose for which it was derived or for which it is to be used.

The 80% subject data points indicate greater tolerance variation as a function of frequency than do either the 50% or 20% subject data. It is reasoned that certain subjects are so critical to vibration from a passenger viewpoint that even low intensities where frequency effects become masked are considered objectionable.

Subjects which are able to withstand higher vibration intensities will become more aware of frequency effects through response of body organs and members and their effect on psychomotor performance.

Subjects which have higher motivation or which are required to perform certain tasks which require considerable attention will normally accept higher vibrational intensities.

Since we are interested in comparing the shapes of the tolerance curves rather than its levels and since military crews flying LAHS condition can be considered motivated, are accustomed to high intensity vibration inputs, and occupied with a variety of tasks, it was assumed that the 80-percentile results would provide the more meaningful comparison.

Figure 50 provides a comparison of shapes of the tracking error performance curves with the objectionable discomfort curves derived in Reference 53 with the incorporation of the seat transmissibility characteristics of Figure 49. It is interesting to note the fairly good agreement, especially for the case of lateral vibration.

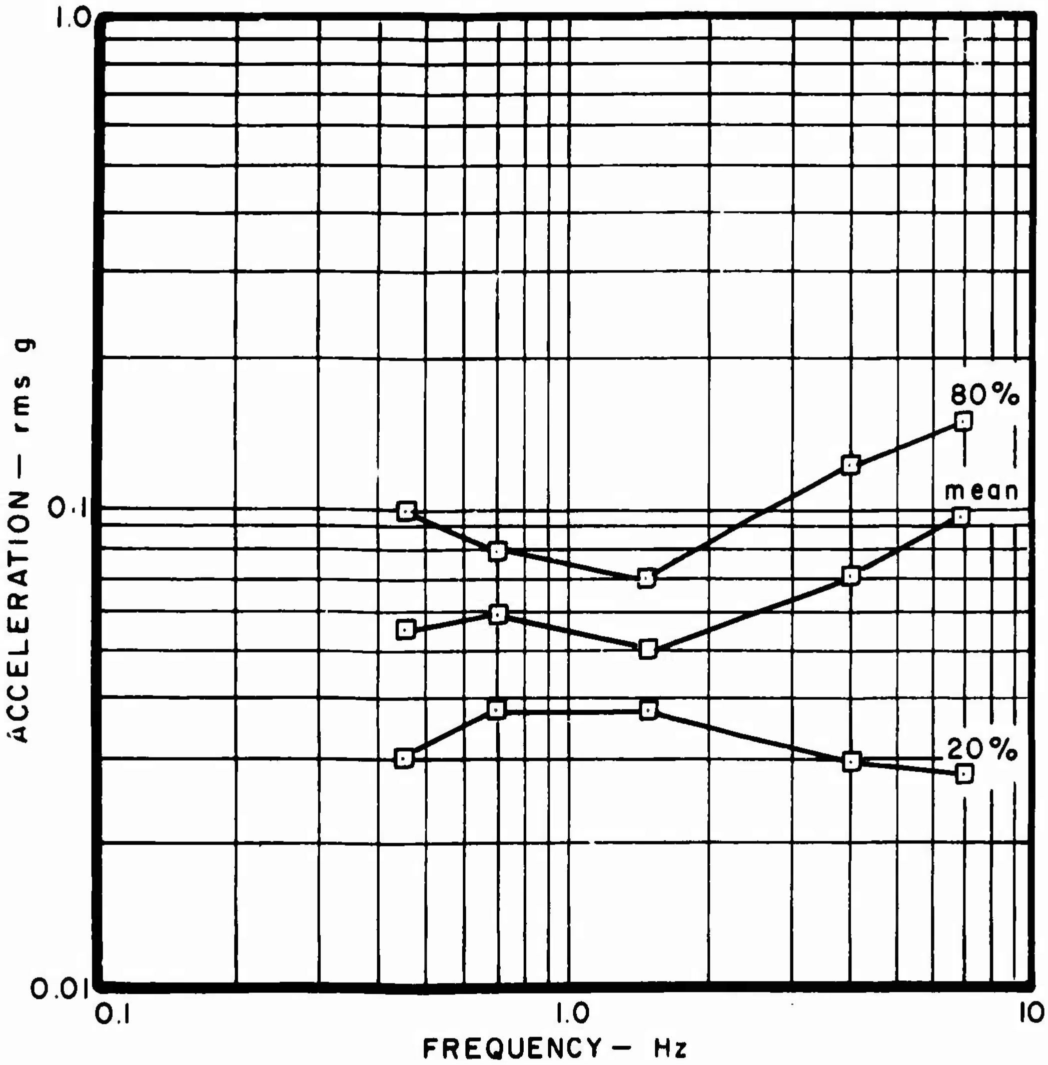


Figure 45. Subjective Objectionable Response to Lateral, Variable Amplitude Vibration (Test 7, Ref 53 and 61)

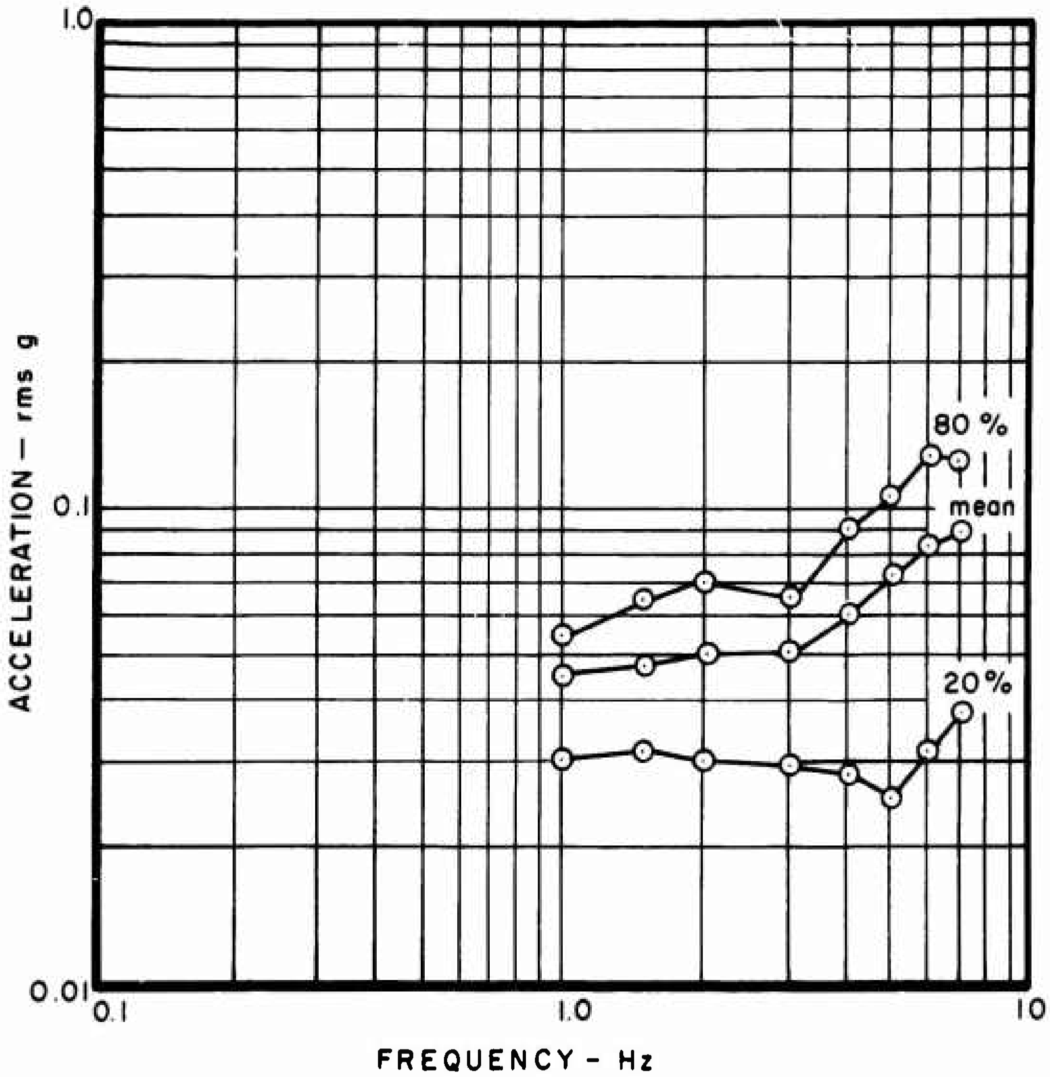


Figure 46. Subjective Objectionable Response to Lateral, Variable Amplitude Vibration (Test 5, Ref 53 and 61)

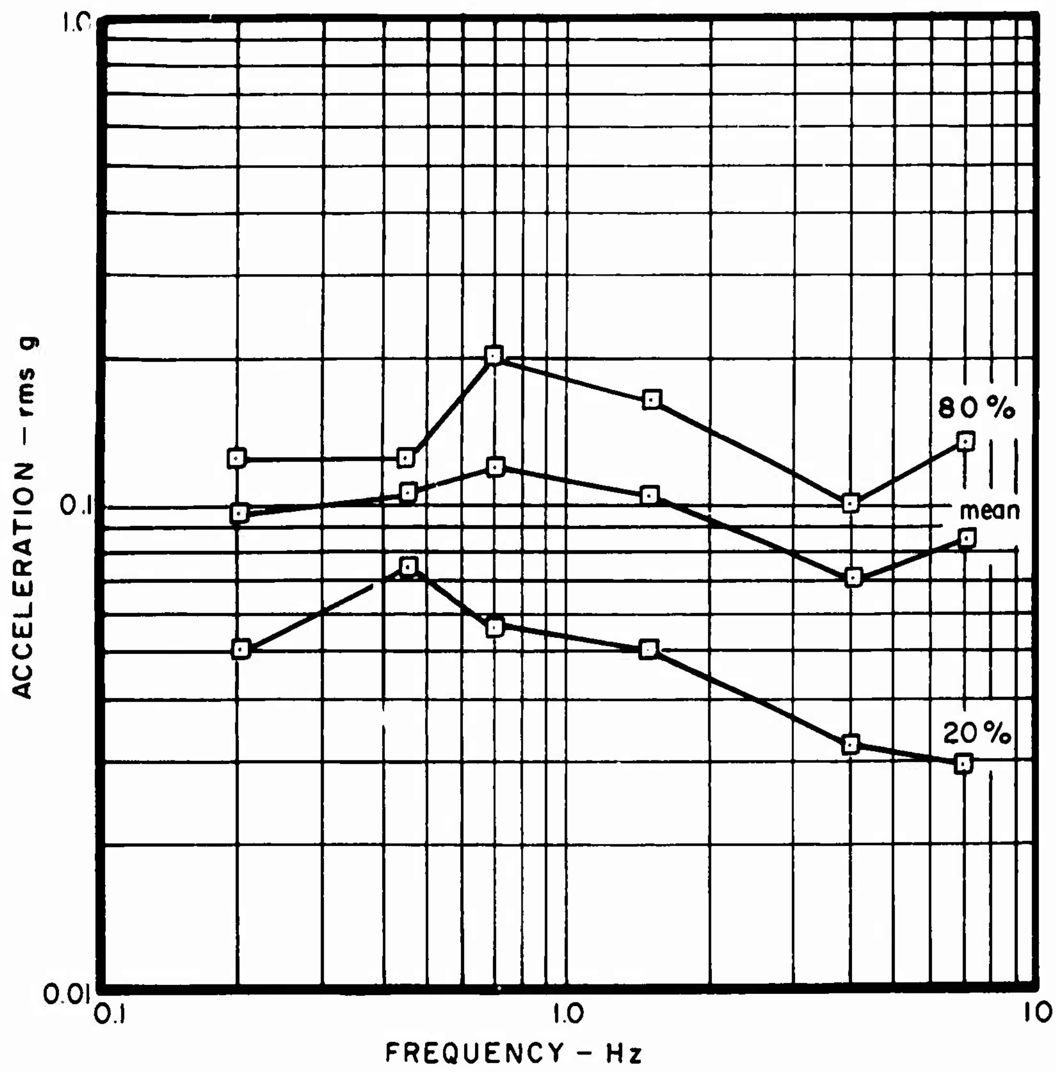


Figure 47. **Subjective Objectionable Response to Vertical, Variable Amplitude Vibration (Test 8, Ref 53 and 61)**

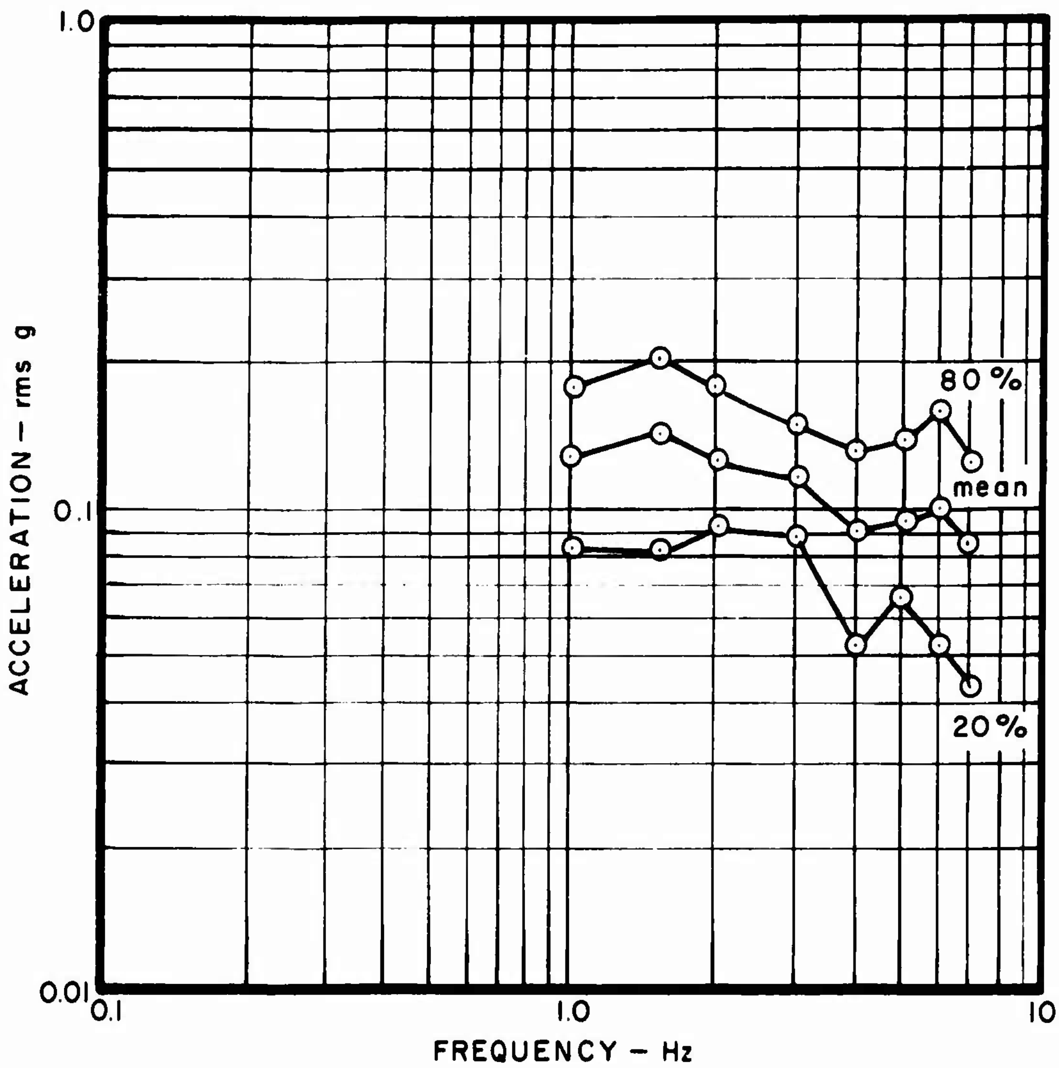


Figure 48. Subjective Objectionable Response to Vertical, Variable Amplitude Vibration (Test 2, Ref 53 and 61)

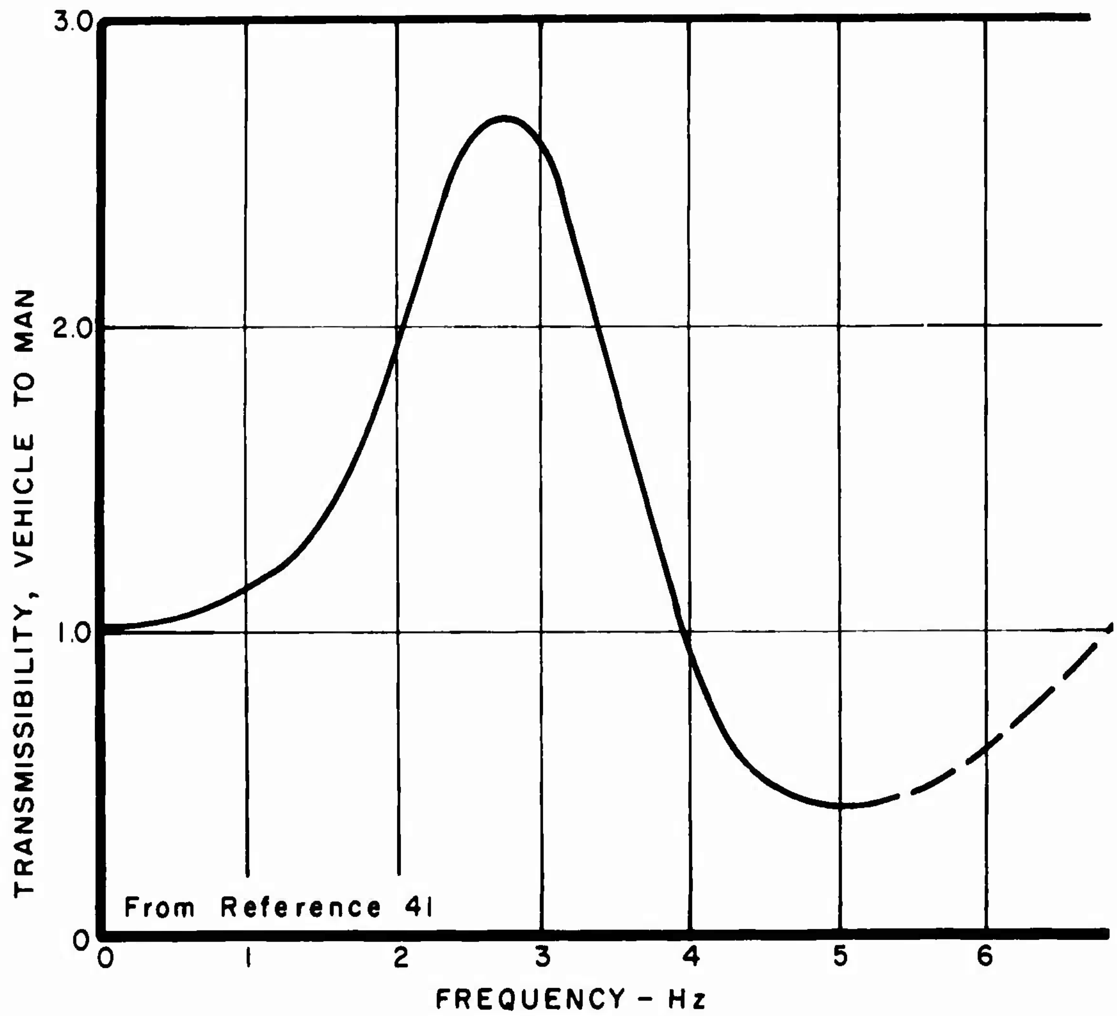
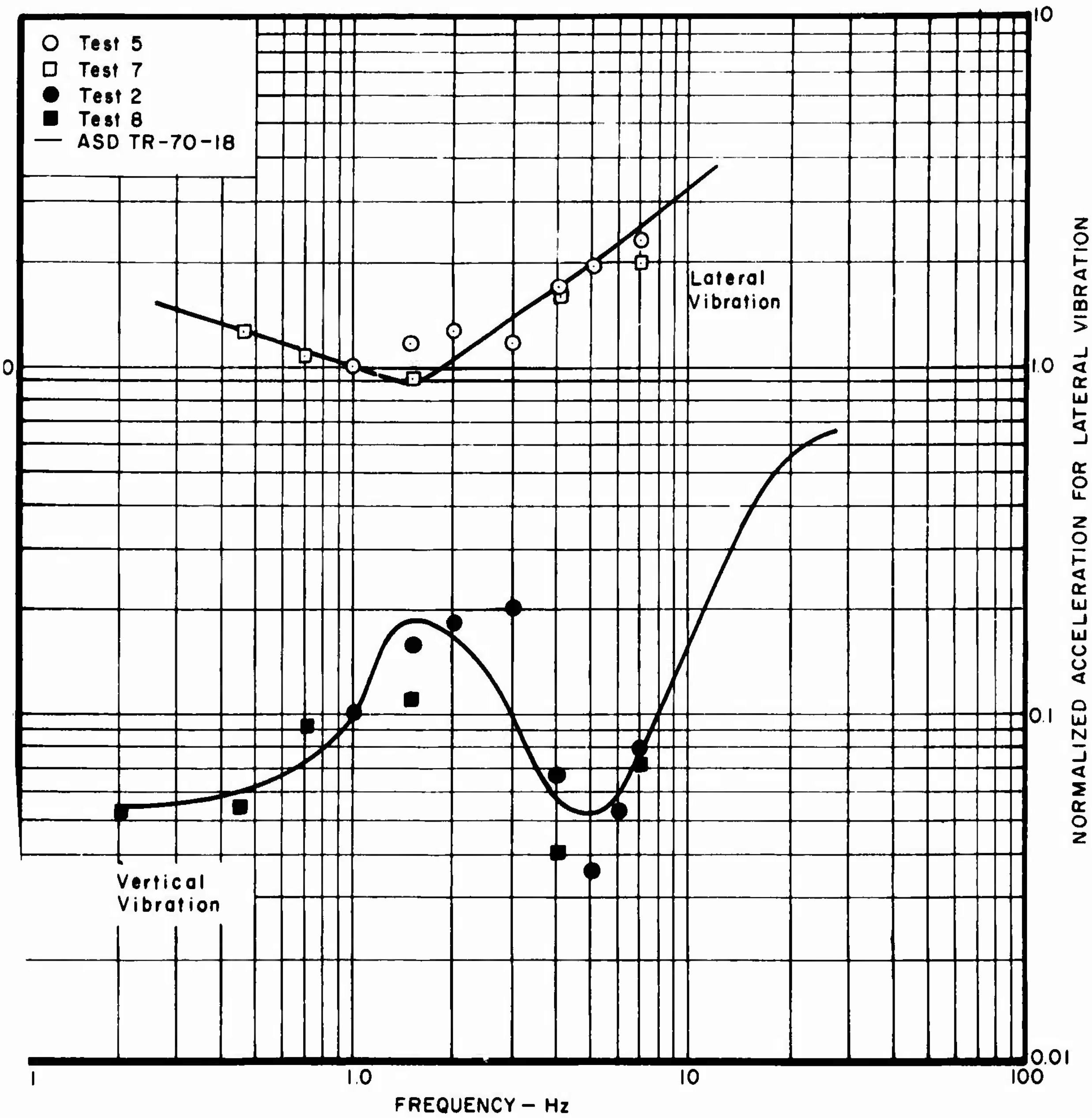


Figure 49. Transmissibility Characteristics for a Conventional Foam Cushi



ıre 50. Comparison of Normalized Constant Tracking Error Response Curves and Subjective Objectionable Response Data for Vertical and Lateral Vibration

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DEVELOPMENT OF TRACKING ERROR FREQUENCY RESPONSE FUNCTION AND AIRCRAFT RIDE QUALITY DESIGN CRITERIA FOR VERTICAL AND LATERAL VIBRATION

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13. ABSTRACT

Experience has shown that the aircraft gust sensitivity index $\bar{A}$, defined as the rms acceleration response per unit of rms gust velocity does not provide a consistent measure of ride quality. A ride quality analysis method which includes the effects of vibration frequency and exposure time on human discomfort or performance has been available. This method, however, has been plagued by the lack of clearly defined human frequency response curves and vibration tolerance criteria.

This report presents the results of a study of available experimental literature in order to more clearly define the shape of frequency response functions for human psychomotor performance under vertical and lateral vibration conditions. The performance frequency response functions as developed are based on a constant tracking error and are used in the calculation of a human performance index for some aircraft. Evaluation of human performance index values and associated crew effectiveness estimates are used to determine ride quality criteria in terms of exposure time and crew tolerance levels for vertical, lateral, and combined-axes vibration inputs.

Appendix II presents a comparison of the shape of vertical and lateral performance curves derived in this study with vertical and lateral objectionable discomfort curves derived independently for commercial transport passenger ride quality criteria development. By allowing for soft seat versus hard seat responses, close general agreement in the shapes of the frequency response curves is noted.

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Vibration exposure time						
Acceleration						
Frequency effects						

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